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Appendix A

Literature Review Report on Technical and Economic Aspects of HV Overhead and Underground Cable Transmission Lines

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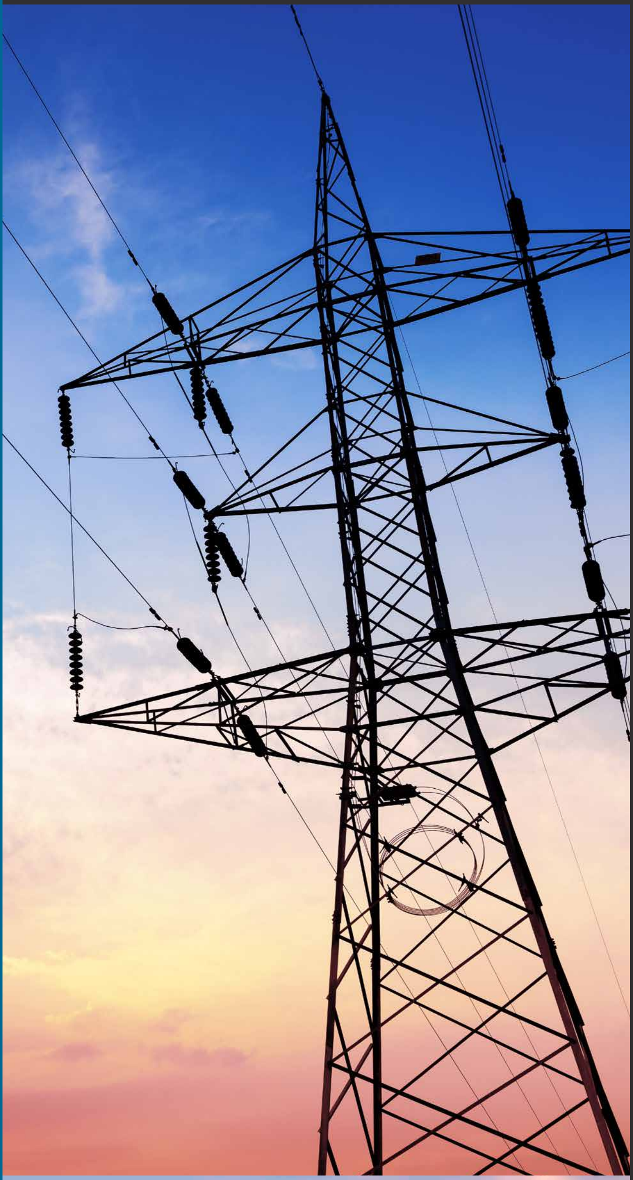

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Abstract

This report presents a systematic review of recent literature on the technical and economic aspects of overhead and underground cable electricity transmission lines. The study aimed to provide a comparison of overhead and underground cable lines on these aspects. The study reviewed literatures published since 2012 from academia including web of science, IEEE explore and Elsevier etc, and also some CIGRE and EPRI documents. Based on the literature review, it is found that the power transfer capability of overhead (OH) lines can be improved by using multi-circuits, multi-voltage lines, and High Temperature Low Sag (HTLS) conductors. For underground (UG) cables, two cables per phase may require to match the capacity of the OH line. However, number of cables can be reduced by employing DC system in place of AC system. Also, the burial depth of HV cables and the improved laying conditions using proper backfills may improve the thermal conditions of UG cable. UG cable system has less disruption to traffic, good protection from bad weather conditions and third-party disturbances. Therefore, UG cables appear to have higher reliability than OH line. However, the outage duration with UG cable can be much longer than the OH line due to difficulty in accessing the cable system. HVDC cables may show even better reliability than their AC counterpart due to their better performance at elevated temperatures. Also, UG cable has advantages of better aesthetics and less magnetic field on ground level (if buried at proper depth) than OH line.

The life of both OH line and UG cable may be affected by their design and operating conditions. In case UG cable, the external environmental factors and the location or route where the cables have been installed influence the cable end of life. While for OH lines weather and other external conditions significantly affects their life.

In terms of project planning and design, the UG cable projects may take much longer time than the OH line projects due to extensive construction requirements for UG cable projects. However, the approval of UG projects could be faster than the OH line projects due to increased public acceptance.

The initial capital cost of UG cable projects can be considerably higher than the OH line projects. However, the operation and maintenance cost of OH line projects may go higher than the UG cable project. The life cycle costs of UG cable are typically 2 to 6 times higher than the OH lines due to high capital costs of UG cable projects. However, the cost of UG cable can be minimized by using of multi-utility tunnels.

1.

Introduction

This literature review focuses on technical and economic aspects of overhead (OH) and underground (UG) transmission lines ranging from 110/132 kV to 500 kV. The outcome of this literature review will be used to provide a comparison of OH transmission line and underground (UG) transmission cable. The literature research scope is broken down in the various aspects of OH and UG transmission lines as follows:

1. Technical Aspects

a. Design Characteristics
b. Reliability Performance
c. Construction Requirements
d. Operating and Maintenance Requirements
e. End of Life Requirements
f. Electro Magnetic Field (EMF)

2. Economic Aspects

a. Project Planning and Pre-Design
b. Design, Approvals and Specification
c. Maintenance and Operation
d. Line Losses
e. De-commissioning Costs

To provide a systematic review, Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology is adopted for guiding the literature review process, including data source selection, publication search, publication selection and summary [1].

The searches were primarily focused on the electrical engineering/ power system databases for a 10-year period between 2012 and 2023.

This report is broken up in the following sections:

1. Introduction
2. PRISMA methodology
3. Findings - a brief summary of all selected publications
4. Discussion (OH lines)
5. Discussion (UG cables)
6. Summary of Findings
7. References

It should be noted that Purposeful reference material and what is commonly referred to as "Grey Literature" were not included in the sources for this review. This material will be referenced separately in the main report that accompanies this Literature Review and largely comprises reference documents from industry, such as:

a. Reference books and major reports from the leading electrical engineering industry based research organisations of CIGRE and EPRI including
- CIGRE Green Books Overhead Lines International Council on Large Electric Systems
- (CIGRE) Study Committee B2: Overhead Lines. Springer Reference.
- CIGRE TB 680 – Implementation of Long AC HV and EHV Cable System. CIGRE, 2017.
- EPRI Underground Transmission Systems Reference Book. Electric Power Research
- Institute, 2015.
- EPRI AC Transmission Line Reference Book 200kV and Above, 2014 Edition

b. Standards, reports and reference material from the industry sources including Australian and international Transmission System Operators, AEMO, AEMC, Federal, State, and local Government bodies.

The "Grey Literature" have synthesized a number of research papers to the time of publication and will be covered separately.

This literature research focusses on other Significant or Relevant Research Material (SRM) which may be more recent than the reference book publication or can provide to contribution to the technical and economic aspects of OH transmission line.

2.

PRISMA Methodology

2.1 Eligibility Criteria (Inclusion & Exclusion):

2.1.1 Inclusion criteria:

- Studies which cover construction and structures used on overhead transmission line and underground cables, e.g., specialised structure designs to address visual amenity and/or ongoing land use
- Studies about economic aspect of overhead transmission line and underground cables, such as whole-of-life cost and operational factors (e.g., initial construction costs, social licence costs, ongoing maintenance and support of infrastructure, operational reliability and resilience, costs of end-of-life asset demolition)
- Voltage level in the range of 110/132 kV – 500 kV
- Published between 2012-2023

2.1.2 Exclusion criteria:

- Duplicated studies/publications
- Studies that are irrelevant to the scope of this review

2.2 Information Sources

Considering that this topic is in the field of electrical engineering/power system, the databases that contain the most relevant publications are selected, they are IEEE, Elsevier, MDPI, Springer Nature, IOP and Wiley.

2.3 Search Strategy

Critical terms are identified to be closely relevant to this topic, then they are combined in the search using “AND” and “OR” logic to reduce the number of search results. The terms, logic and scope used in the search are:

- “Overhead Transmission line (topic) and Construction (abstract)”
- Or “Overhead Transmission line (topic) and Condition assessment (topic)”
- Or “Overhead Transmission line (topic) and Lifecycle management (topic)”
- Or “Overhead Transmission line (topic) and HVAC (topic)”
- Or “Overhead Transmission line (topic) and HVDC (title)”
- Or “Overhead Transmission line (topic) and Investment (topic)”
- Or “Overhead Transmission line (topic) and Economic (abstract)”
- Or “Overhead Transmission line (topic) and Whole of life cost (topic)”
- Or “Overhead Transmission line (topic) and Loss (title)”
- Or “Underground Cable (topic) and 500kV (topic)”
- Or “Underground Cable (topic) and Construction (topic)”
- Or “Underground Cable (topic) and Condition assessment (topic)”
- Or “Underground Cable (topic) and Lifecycle (topic)”
- Or “Underground Cable (topic) and HVAC (topic)”
- Or “Underground Cable (topic) and HVDC (topic)”
- Or “Underground Cable (topic) and Investment (topic)”
- Or “Underground Cable (topic) and Economic (topic)”
- Or “Underground Cable (topic) and Whole of life cost (topic)”
- Or “Underground Cable (topic) and Loss (topic)”
- Or “Underground Cable (topic) and Case study (topic)”
- Or “Underground Cable (topic) and Project (topic)”

2.4 Data Collection Process

Based on the aforementioned eligibility criteria, information sources and search strategy, publications are identified as per the procedures presented in the flow chart in Figure 1. According to the search strategy, 511 publications about OH transmission line and 659 publications about UG cables are found through Web of Science, out of which 109 for OH and 116 for UG transmission lines are determined to be potentially contributing to the scope of this study after screening all publications’ titles and abstracts. Then, these shortlisted publications are reviewed in detail and finally 24 publications for OH line and 28 publications for UG cable are selected for further discussions. Also, a CIGRE document [2], [3] on UG cable is included in the discussion because of its relevance to the scope of the project.

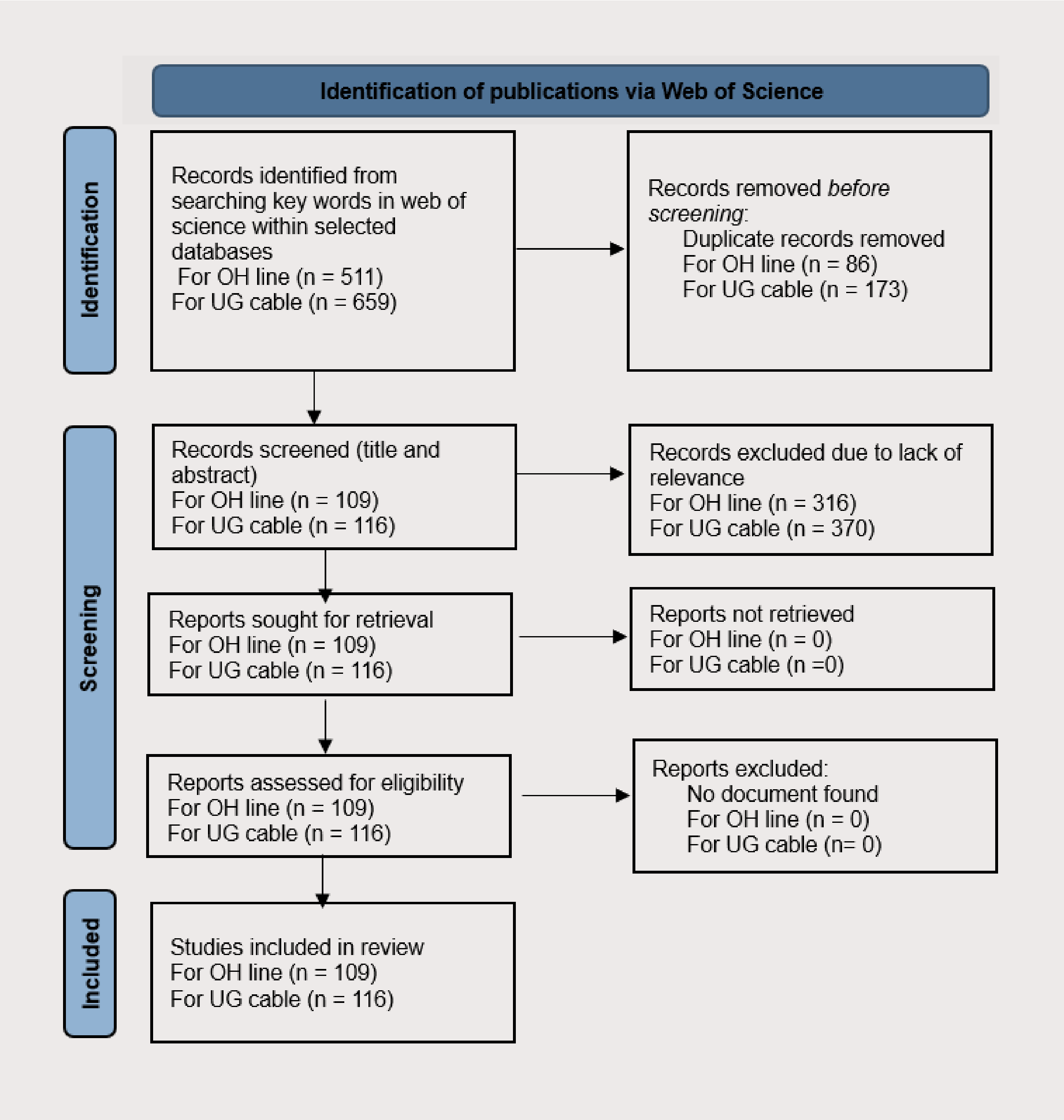

Figure 1 Prisma flow diagram of studies to be included in the systematic literature review

3.

Findings

As per the PRISMA approach, 109 papers have been screened and selected for detailed review for OH lines and 116 for UG cables. All these selected papers have been reviewed in detail to extract useful information, which covers various technical and economic aspects of OH and UG transmission lines. Table 1 and Table 2 gives a summary of the studies along with relevant aims and contributions to the scope of the review for OH lines and UG cables respectively from 24 publications for OH line and 28 publications for UG cable.

Table 1 – Study Summary with Voltage level, Aim of Publications and Contribution to the Scope of Review of OH lines.

Study	Voltage type & level	Aim of publication	Contribution
4	**HVAC/400 kV**	This paper presents a computing approach for determination of the magnetic flux density under OH line	Shows computed magnetic flux density of selected 220 kV and 400 kV OH lines
5	**HVAC** **110-330 kV**	This paper presents a holistic risk-based maintenance decision-making methodology for transmission overhead lines and its practical implementation. The methodology is implemented based on Estonian transmission system	Provides data about outage duration at different voltage levels.
6	**HVDC**	This paper presents an asymmetrical design of VSC-Based HVDC transmission lines	New design by adjust insulators to achieve higher power transfer capacity
7	**HVAC&HVDC** **420 kV**	This paper investigates the audible noise and corona losses of DC circuits on hybrid overhead lines, and conductor surface treatment to reduce audible noise	A real-case example of hybrid HVAC/HVDC 420kV ±400kV line in Austria
8	**HVAC&HVDC** **380 kV, 420 kV**	This paper presents benefit analysis of a hybrid HVAC/HVDC transmission line based on a Swiss case study. It is demonstrated that the hybrid conversion is beneficial since it can lead to reduction in the AC line loading, lower operating costs and increased utilization of the network infrastructure by enabling higher transit flows	A real-case study to demonstrate the benefits of hybrid HVAC/HVDC, drawback is efficiency decreases due to high converter losses
9	**HVAC 110, 220, 400kV**	This article presents an analysis of the use of multi-circuit, multi-voltage overhead lines as a compromise between ensuring the system's safe operation by increasing the transmission network capacity and managing the constraints related to its expansion.	1. It presents discussions on key factors in the design of HVAC multi-circuit, multi-voltage lines. 2. A list of real cases using multi-circuits, multi-voltage OH lines in Europe is presented.
10	**HVDC 800 kV**	Model of HVDC overhead transmission lines with covered conductors is presented. Results show that covered conductors can restrain ion flow field obviously.	Proves that covering conductor with a layer of insulation could restrain the ion flow significantly.
11	**HVAC 110 kV**	This paper presents a new tower design for OHAC 110 kV, called 110STJ tower that is of double circuits and access other lines with single π type, which is used in China for the first time.	Introduces a new tower design for 110 kV OHAC 110 kV

Study	Voltage type & level	Aim of publication	Contribution
12	**Hybrid HVAC/HVDC**	Hybrid HVAC/HVDC has various AC/DC interaction phenomena. The paper deals with the AC impact on the DC power circuits switched off for maintenance purposes.	transposition of the AC power circuits of the hybrid AC/DC transmission line is an efficient measure for the reduction of the induced currents in the de-energized DC conductors, but on the other hand the AC line transposition can cause the significant increase of the touch voltages on the de-energized DC conductors and can cause the violation of the safety requirements for the maintenance work.
13	**HVAC**	This paper presents the state of the art in monitoring technologies that can be used to identify thermal stress on OHL conductors, including the issues and challenges in monitoring.	Provides a comparison of conventional conductors and modified conductors.
14	**HVAC/HVDC** **400, 500 kV**	This paper seeks to propose a hybrid AC/DC power transmission network by the addition of superimposed HVDC lines overlaying existing European transmission corridors.	HVAC superposed with HVDC to save cost Cost details are illustrated with tables for comparison purpose.
15	**HVAC/HVDC, 500 kV**	this paper conducts a thorough Life-cycle cost analysis of HVDC in Turkey. A comparison of this cost between HVDC and HVAC is also presented.	Cost details of HVDC and HVAC are presented, which are valuable for economic analysis of HV lines.
16	**HV**	A project CALAJOULE, co-financed by the Italian Ministry of Economic Development in the framework of the "Ricerca di Sistema" programme, aims at proposing innovative solutions for overhead line conductors for the containment of Joule power losses. This paper presents the main characteristics of the innovative conductors along with the expected benefits deriving from their use in place of the traditional ones.	Introduce a new type of conductor that reduces Joule losses.
17	**HVAC**	This work presents cost evaluation of current uprating of overhead transmission lines by using Aluminium Conductor Steel Reinforced (ACSR) and High Temperature Low Sag (HTLS) conductors. The evaluation method is carried out based on twofold and fourfold ampacities, under both normal and stressed operating conditions. The test case is a 230-kV, double-circuit, transmission lines using 1272 MCM ACSR conductors.	This works details cost evaluation in five cost components, i.e., demolition cost, construction and installation costs, conductor cost, cost of energy losses, and land cost.
18	**NA**	In this paper, a D-distance risk factor was proposed to prioritize high-voltage transmission lines from high to low risk in transmission line maintenance and renovation management.	This paper presents a comprehensive condition assessment for OHTL. TBD
19	**HVTL/UGTL**	in this paper, economic analysis of power transmission lines using interval mathematics has been studied. Life cycle costing studies are performed using net present value analysis on a range transmission lines used in India and the results are analysed. A cost break even analysis considering right of way costs was carried out to determine the point of economy indifference.	This works provides a comparison of life-cycle cost analysis between HVTL and UGTL at 132kV, 220 kV and 400 kV.
20	**HVAC**	The paper presents some of the results of the CALAJOULE project co-financed by the Ministry of Economic Development in the framework of the "Ricerca di Sistema" programme.	This paper presents an innovative conductor that reduces Joule loss remarkably.
21	**HVTL**	Highly Efficient Overhead Line Innovative Conductors with Reduced Joule Power Losses.	Provides state-of-art presently adopted conductors for power lines, and introduced two innovative conductors.

Study	Voltage type & level	Aim of publication	Contribution
22	**HVDC**	HVDC System Solutions.	This paper introduces high-level basics of LCC and VSC HVDC solutions. TBD
23	**HVAC, 380 kV**	Innovative insulated cross-arm: requirements, testing and construction.	New compact tower design but there is a lack of more detailed information.
24	**HVAC/HVDC**	Integration Enhancement of Grid-Connected Wind Farms Using HVDC Systems: Egyptian Network Case Study.	To integrate a wind farm into Egyptian grid, three proposed plans for this 4000MW 75 km transmission line are proposed, and their economic analysis is compared.
25	**HV**	The paper deals with a comparative analysis of the technical (mechanical and heating limitations) and economic efficiency of using conductors of different types, which is based on two actual overhead line models.	The comparison results suggest that the use of HTLS conductors replacing the traditional type conductors can be more economically justified if the price of conductors with composite core is reduced, yet at the same time, it can be one of the possible solutions for increasing the limited capacity of the existing overhead lines
26	**HVAC**	Technical-economic comparison between three and four-conductor bundled 380 kV OHLs.	A very specific comparison, may be not very useful.

NA refers to no relevant information is found in the publication.

Table 2 – Study Summary with Voltage level, Aim of Publications and Contribution to the Scope of Review of UG cables.

Study	Voltage type & level	Aim of publication	Contribution
27	**Range of voltages**	Covers the technical aspects of Underground Transmission Systems.	Thoroughly presented the technical aspects of underground cable system.
2	**Range of HV and EHV**	The design, challenges, installation, maintenance, and monitoring of HV and EHV transmission cables are presented.	Protection system, harmonic resonance, magnetic field, testing, installation, transportation, quality assurance, and monitoring of cable system is presented. Also, experience of many cable projects from different countries are shared.
3	**150 kV**	Dynamic rating techniques are described.	Dynamic rating systems is discussed for 150 kV OH lines and UG cable.
28	**Range of voltages**	Technical aspects of HVDC cable system.	Fundamentals, main principles, design, space charge and life modelling of extruded HVDC cable system is presented.
29	**220 kV**	This paper discuss the specific challenges of power cable monitoring in a cable tunnel and the problems that are encountered due to design ignorance.	A case study is discussed.
30	**230 kV**	This paper highlights the use of UG power cables in conjunction with overhead lines, where the reactive power requirement of overhead line is compensated by UG power cables.	A case study is discussed.
31	**138 kV**	This paper summarizes the design choices and project challenges considered during implementation of six cable projects on the Delmarva peninsula in 2012 and 2013 that significantly expanded the reliability of the utility's power system.	Discussed cable design challenges. Sometimes only limited suppliers are available for a particular type of cable. Sometimes termination failures occur in cable system. In case of fault, the restoration time of cable can be much longer (days to weeks) than for overhead (hours to days). Two smaller power cables can be used to isolate the failed cable and maintain partial power transfer with other cable. However, two smaller cables require twice terminations. A system that has more accessories will inherently have lower reliability than a system with fewer accessories. Therefore, adding two cables per phase for shorter circuits does not always provide benefits in terms of reliability or shortened restoration time. Cables often have lower normal ratings than other transmission equipment, particularly overhead lines, but much higher emergency rating capabilities – particularly short-duration emergencies -- due to the long thermal time constant of cables and the mass of earth in which they are installed. The typical challenges of underground projects such as traffic control, pavement restoration, extensive permitting, easement procurement, etc.
32	**225 kV**	The paper presents the challenges of the construction of extra-long high power underground cable transmission lines. Advantages and disadvantages of different cable bondings are highlighted.	A novel direct cross bonding for 225 kV cable system is presented.

Study	Voltage type & level	Aim of publication	Contribution
33	**NA**	The paper presented the Lifecycle Cost (LCC) analysis of Multi-purpose Utility Tunnel (MUT) and buried utilities LCC by considering the influencing factors.	Life cycle cost of multi-purpose utility tunnel is estimated. Mainly discussed about Multi-purpose Utility Tunnel. Discussed about finance and cost sharing between multiple utilities in same tunnel. A case study of 250 m long tunnel is discussed. The cost of installation of 2 buried cables, which occupies space 1 meter wide in an area with population density of 27,078 persons per km^2 is mentioned to be $759,000. The operational (maintenance) yearly cost of buried cables is mentioned as $31,875 and tunnel maintenance cost is mentioned $ 6000/year. The lifecycle cost for buried cables are mentioned as $4,639,100. If Same cables are installed in multi-purpose utility tunnel, the lifecycle cost mentioned is $2,861,555.
34	**110 kV**	This paper developed an algorithm for decision-making mechanism for utility tunnel construction cost allocation by considering some cost allocation indexes.	Paper presented comparison between the cable laying costs in utility tunnel and direct laying. The service life of cables in utility tunnels are 15 years more than the cable directly layed.
35	**110 kV**	The paper presented a method to estimate the life time cost of different types of power lines. It considered the construction, maintenance and fault elimination costs depending on each power line type (OH, UG, high OH, and isolated wire OH).	Paper presented Latvian case studies to compare the construction and operating costs, and the customer cost of reliability for a 30 kms transmission line. Comparison is made between 30 Kms overhead line and 24 Kms overhead + 6 Kms underground cable options. The annual construction, maintenance, and failure cost for overhead line option is estimated as $ 29,568 while it is estimated as $28,776 for the overhead + underground cable option.
36	**NA**	This paper model the uncertainties of underground transmission cable for asset renewal projects considering the common risks and uncertainties associated with cable such as financial costs, project timing, real estate and environmental issues.	This paper discusses the common risks (related to the financial costs, project timing, real estate and environmental issues) and uncertainties associated with underground transmission cable asset renewal projects. Paper mentioned that there can be little to no control over the surrounding environment where underground cables get installed. "Not-In-My- Backyard" (NIMBY) objections from the public. The difficulty in obtaining new easements can result in drastically higher construction costs and can affect the financial viability of the asset sustainment project itself. The time frame required for the planning, construction and commissioning of a typical new underground cable circuit (including planning, route identification, engineering and construction) typically requires at least from 3 to 7 years, depending on the route location and the scope of the project. Many of the initial assumptions (budgetary, revenue sources, routing, technical, etc.) that were made originally at the time when the project was initiated often would often change throughout the project execution stage. This can result in cost overruns and affect the economic viability of the projects. The combination of normalized financial and non-financial possibility distributions into one resultant aggregate distribution represents the overall possibility distribution for the project, which in turn, can be compared to other developed projects to facilitate their ranking.

Study	Voltage type & level	Aim of publication	Contribution
37	**Reliability assessment tool for underground cable and overhead lines**	Reliability assessment tool for underground cable and overhead lines.	This paper presents a reliability assessment tool for underground cable and overhead lines considering attributes such as failure rates, repair times and intrinsic features under multiple circumstances and the seasonal variation of load and co-generation within them. The study is supported by the specific data collected from the regional utility companies and operators.
38	**Greenhouse gas emission comparison between HVAC and HVDC**	Greenhouse gas emission comparison between HVAC and HVDC.	The greenhouse gas emissions are compared between the HVAC and HVDC cables for per unit weight (1kg) of cable based on the amount of clean renewable energy carried over one year of operation in a Europe environment. The authors estimated 101,000 tons of greenhouse gasses emission saving per kg of HVDC cables, while it is 40,400 tons per kg of HVAC cables. The most frequent rated voltage of HVDC extruded cable projects in service in Europe is 320 kV. The highest voltage of HVDC extruded cable projects being installed at present is 525 kV DC and belongs to the huge German corridors. The voltage limit of applicability of Cigrè testing procedures for HVDC extruded cables has been recently pushed up from 500 kV of TB 496:2012 to 800 kV of TB 852:2021. The paper also discussed the future HVDC projects of German Corridors project.
39	**Paper discussed the issues and challenges of HVDC cables.**	Paper discussed the issues and challenges of HVDC cables.	The issues and challenges of HVDC cables are discussed considering accessories, higher voltage and power, laying environment (submarine and underground cables), modeling, multiterminal HVDC, operation and diagnostics, recyclable insulation, space charge behavior, testing, thermal stability, transient voltages.
40	**525 kV**	The paper described the development of 525 kV cable, its accessories and comparison with 320 kV extruded DC system.	Authors stated that 525 kV extruded DC cable system can transmit at least 50% more power over extreme distances than the 320 kV extruded DC system. As compared to 320 kV cable system, 525 kV cable system have lower cable weight per installed megawatt (MW) of transmission capacity and higher voltages provide reliable transmission and low energy losses.
41	NA	Paper discusses the extruded power cable technology for HVDC applications.	Techniques for measuring space charge and conduction are described for HVDC cable system.

Study	Voltage type & level	Aim of publication	Contribution
42	**150/400 kV**	Paper presents detailed information on life cycle stages of overhead line and underground cables.	Paper discusses how large are the impacts resulting from power losses in the equipment and how large is the share of impacts associated to each of the other life cycle stages of overhead line and underground cables: raw materials production, transportation, installation, maintenance, and dismantling. In addition to losses, processes included are for lines—production of materials for foundations, masts, conductors, and insulators and for cables— production of cable and cable trace. Installation (excavation, etc.) use/maintenance (replacement of parts, inspections) and end of life are also included for both overhead and cable systems. For overhead lines, among all impact categories, material for masts and conductor causes maximum CO2 emissions followed by foundations, installation activities, and at last maintenance operations. The end of life has a negative contribution in all impact categories, which means that the benefits of recycling of metal parts in the masts and conductors outweigh the sum of impacts generated by other end of life processes. For underground cable also, cable material production causes maximum CO2 emissions followed by cable traces which involves removal of old asphalt and building a new layer of sand, cement, and asphalt where the cable is to be installed. For land cables the impacts of end of life represent a cost (causes CO2 emissions) rather than a benefit.
43	**120/230/315 kV**	Underground cable management methodologies, managing and their renewal challenges and issues.	Paper states that due to inaccessibility, physical condition of cable is difficult to ascertain, taking cable sample for condition monitoring is difficult. There should be a systematic framework to evaluate and rank asset renewal investment projects based on modeling uncertainties (size of load lost, number of customers disconnected, critical loads, consequential damage, safety and environmental consequences) and on determining the relative importance (considering risks such as safety, financial, reliability, and environment) of a particular transmission line circuit in the power system as it affects the bulk power system reliability. Making such framework would be challenging because of lack of ability to accurately determine the condition of many underground cable, lack of knowledge in the failure probability for certain cables, difficulty in quantifying the financial consequence of asset failures, limitations in system reliability considerations, and lack of consideration of the time required for implementing the asset renewal / replacement plan.
44	**NA**	Comparison between superconducting cable and underground cable.	Comparison is made between superconducting cable and underground cable considering the factors such as investment cost, reliability, energy loss, capacity, environmental impact when connects two substations using these options.
45	**Na**	Presented a study to find the optimized maintenance and replacement cycle of underground cables.	This paper examined the actual failure rates of the underground cables, the costs of maintenance and repair of cables, and the costs caused by their failures.
46	Na	Total cost of production, installation, and operation of two types and sizes of cable is presented in this paper.	A detailed model for the calculation of the life-cycle cost of cable ownership is presented.

Study	Voltage type & level	Aim of publication	Contribution
47	**220/380 kV**	Techno-economic comparison is made between high temperature superconductor (HTS) transmission cables, overhead line, and XLPE underground cables.	In this paper techno-economic comparison is made between high temperature superconductor (HTS) transmission cables and other available alternatives such as overhead line and XLPE underground cables. As compared to other options, HTS cables are: economic, underground, higher power capacity, lower losses, reduced magnetic field emissions in (existing) OHL, compact: less occupation of land and less permits needed, a possibility to keep 380 kV voltage level in the grid for as long as needed. Different options of transmission are studied and compared based on number of conductors, power transfer capability and losses associated with each option.
48	**380 kV**	Capital cost, reactive power compensation cost, energy loss cost, burden on territory cost, end of life, operation and maintenance, and random failure costs are compared.	Power loss cost, operations and maintenance cost, commissioning and dismantling cost, repair cost, and overall cost is compared between OH line and UG cable.
49	**380 kV**	Comparison of superconducting 380-kV cables with existing overhead lines and underground cables.	Power loss is compared between OH line, UG cables, and superconducting transmission line.
50	**161 kV**	This paper analyses a junction tower, the interface between overhead lines and underground cables.	Electromagnetic analysis of junction tower with cable system is presented.
51	Up to 800 kV	Comparison of HVDC and HVAC. Many case studies presented and compared.	Paper stated that for overhead point-to-point transmission projects and connecting remote offshore wind farms that are more than 50-100 km away, HVDC is the preferred option for distances greater than 300-800 km. The paper covers the following aspects: technical and economic comparison of HVAC and HVDC systems; investigation of international HVDC market size and conditions. The contemporary operational challenges such as the ownership of Multi-Terminal DC (MTDC) networks are discussed. Subsequently, the required development factors, both technically and regulatory, for proper MTDC networks operation are highlighted, including a future outlook of different HVDC system components.
52	Range of voltages	This paper presents an update on superconducting transmission lines.	Technical and the socio-economic aspects of superconducting transmission lines are discussed in detail.

4.

Discussion (OH lines)

This discussion will be based on the 24 publications that are selected based on PRISMA approach. Note that is discussion will not cover a comprehensive basics of the technical and economic aspects, instead, this discussion intends to provide some potentially novel or new experiences that may benefit network operators.

4.1 Technical aspects

4.1.1 Design aspects

Power Transfer Capability

1. ***Multi-circuits, multi-voltage lines***

   A way to increase power transfer capability based on current transmission infrastructure is to expand current overhead transmission line into multi-circuits, multi-voltage lines. Practical examples could be found in Table 3 [9].

Table 3 – Selected examples of multi-voltage transmission lines in the world [9]

No.	Country	Number of Circuits	Rated Voltage	Actual Length of the Multi-Circuit Section	
			kV	km	%
1	**Denmark**	**3**	400 + 2 x 150	118	12.8/6.5
2	**Denmark**	**2**	400 + 150	215	23.3/11.9
3	**Denmark**	**2**	400 + 132	7	0.8/0.7
4	**Germany**	**3**	380 + 2x220	38.5	-
5	**Germany**	**3**	380 + 2 x 150	7.5	-
6	**Germany**	**3**	380 + 2 x 110	135.7	-
7	**Germany**	**2**	380 + 110	4.6	-
8	**Germany**	**2**	220 + 110	1.7	-
9	**Montenegro**	**2**	400 + 110	40	14/5.8
10	**Netherlands**	**4**	2 x 380 + 2 x 170	-	-
11	**Lithuania**	**2**	330 + 110	2.5	0.1/*
12	**USA**	**2**	345 + 230	-	-
13	**USA**	**2**	230 + 115	-	-
14	**Switzerland**	**3**	2 x 380 + 132	-	-
15	**Poland**	**4**	2 x 400 + 220+110	31.2	0.5/0.4/-
16	**Poland**	**3**	2 x 400 + 220	4.8	*/*
17	**Poland**	**3**	400 + 2 x 110	6.5	0.1/-
18	**Poland**	**2**	400 + 110	43	0.7/-
19	**Poland**	**2**	220 + 110	7.5	0.1/-
20•	**Poland**	**3**	2 x 400 + 220	~20	0.3/0.3

Note • = build scheduled for the years 2027-2030; * = less than 0.1 %

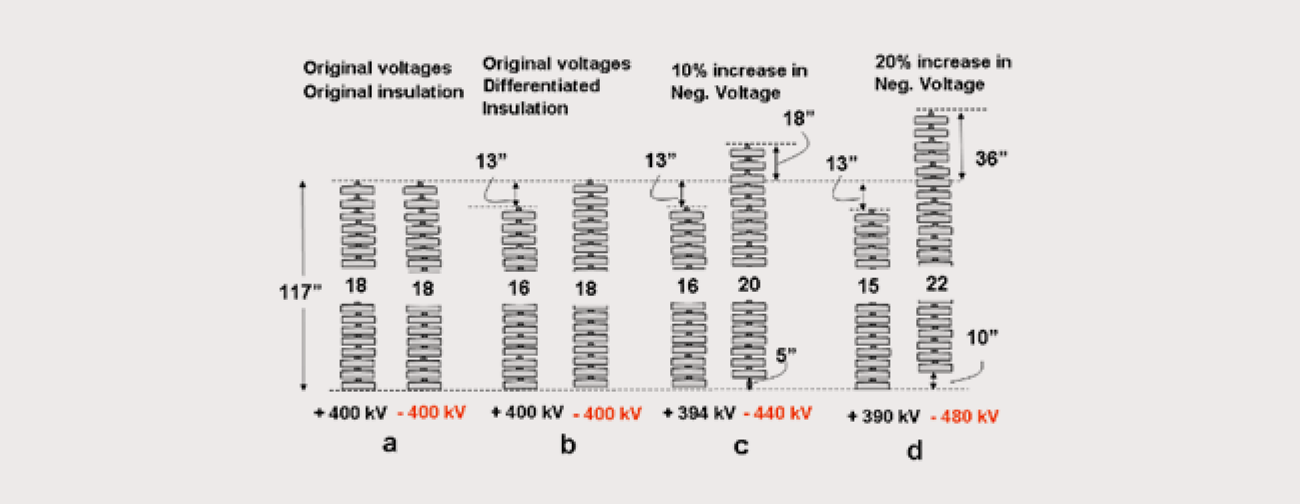

Figure 2 – 400kV example insulation and height adjustments [7]

2. ***Uprating existing HVAC line by replacing ACSR conductors with HTLS conductors***

   There have been various suggestions for improving existing power line networks with the purpose of increasing their throughput capacity as well as the reliability of power supply. This is an important problem that must be considered, especially if the transmission grid requires the prospective expansion of new electrical connections. Therefore, the use of High Temperature Low Sag conductors replacing the traditional type conductors can be one of the possible solutions for the posed problem. In [25], this paper deals with a comparative analysis of the technical (mechanical and heating limitations) and economic efficiency of using conductors of different types, which is based on two actual overhead line model. The results suggest that the use of HTLS conductors replacing the traditional type conductors can be more economically justified if the price of conductors with composite core is reduced, yet at the same time, it can be one of the possible solutions for increasing the limited capacity of the existing overhead lines.

3. ***Hybrid AC/DC***

   Hybrid overhead lines (OHL) are a promising concept to increase transmission capacity without building new lines. However, due to small distance between AC and DC line, an AC ripple would lead to increase in audible noise and corona losses. Conductor surface treatment can be used to reduce audible noise [8].

4. ***HVDC***

   The introduction of overhead DC transmission using VSC (Voltage Source Converter) technology enables the reversal of power direction by changing the current flow rather than altering the voltage polarity. This capability allows for independent design of the poles in HVDC lines, leveraging the differences in insulation strength, generation of radio and audible noise, and perception of electric fields at ground level based on polarity. By doing so, it becomes possible to achieve a negative voltage that is generally 10% to 20% higher than the positive voltage. Consequently, this results in an increase in the MW (megawatt) rating by approximately 5% and 10% respectively. Figure 2 is a picture showing adjustments in insulators to achieve higher negative voltage [7].

Conductors

Traditionally, conventional conductors were made up of strands composed entirely of aluminium alloy. However, in order to enhance their electrical and mechanical properties, the aluminium core of these strands has been replaced with alternative materials like steel or alloy (e.g., ACSR and AACSR). This substitution is necessary because aluminium wire exhibits a high thermal expansion coefficient, causing the core strand to expand rapidly when exposed to high temperatures. To improve power transmission through the line, the conventional conductor has undergone upgrades tailored to specific conditions. These enhancements include the use of different coatings to resist corrosion, altering the shape of the strands to prevent deformation, and modifying the geometric configuration of the conductor to optimize its performance. By making these adjustments, the electrical and mechanical properties of the transmission lines have been improved, strengthening the conductor's ability to withstand challenges such as strong winds (galloping), low wind speeds (aeolian vibration), ice loading, and high temperatures. [13] provides a comparison of conventional conductors and modified conductors in OHL as illustrated in Table 4 and Table 5.

Table 4 – Commonly available conventional conductors in OHL [13]

	Composite material	Function	Advantages	Disadvantages	References
AAC	**Outer: Al** **Core: Al (extra-hard-drawn 1350-1119)**	Most urban areas at short-span lengths.	Good corrosion resistance. Better conductivity than AAAC. Lighter than ACSR.	Poor strength.	[22], [28]
AAAC	**Outer: Al 1350-H19 Core: 6201-181 Al alloy**	Seacoast area More suitable than ACSR in overhead distribution.	Excellent corrosion resistance. Higher tensile strength than AAC. Lower resistance than equivalent ACSR.	Moderate conductivity. Moderate hardness against balding stress. Prone to fatigue failure problem. Present aluminium alloy makes it expensive.	[22], [28], [30]
ACAR	**Outer: Al 1350-H19** **Core: 6201 Al alloy**	Wide transmission line application.	Excellent corrosion resistance. Higher strength. May be consider as a replacement for conventional ACSR.	Lower corrosion resistance than AAAC.	[22], [31]
ACSR	**Outer: Al 1350-H19 Core: Galvanize steel**	Wide usage in long-span transmission lines and rural distribution area. Suitable across rivers. Ice and wind loading area.	Excellent strength and low Sag. Good conductivity. Higher durability compared with AAAC in bending stress.	Maximum operating temperature of 93 °C, limited to heavy load operation. Less conductivity compared with ACAR.	[22], [24]

Table 5 – Types of modified conductor [13]

Group	Type of conductor	Function	Advantages	Disadvantages	References
TW	**ACSR/TW,** **AAC/TW,** **AAAC/TW,** **ACSS/TW**	Application reduces wind and ice load problem.	Improves mechanical and electrical properties of conventional conductor. Lighter than equivalent diameter with conventional conductor. Geometric configuration increases current carrying capacity. Restricts creep over long term service.	Lines up to 16 kV, small conductors may be prone to the corona effect. Manufacturing the geometric configuration for stranding wire machine needs special equipment which may be prone to breaking.	[22], [37], [40]
TP	**ACSR/TP, AAC/TP, ACAR/TP**	Anti-galloping motion and aeolian vibration.	Configuration prevents ice formation. Low power lases.	Limited use for other applications. Lower operating conductor temperature. Costly installation and hardware.	[22], [34], [35]
HTLS	**ZTACIR (with INVAR), GZTACSR, TACSR, ACSS, ACCR, ACCC**	Use in high load operation. Wind area and aeolian wind. Crossing rivet or long distance.	Higher conductivity. Operates in high temperatures. Low potential sag. Lighter. Suitable in extreme weather. Minimum fatigue issues.	Higher installation cost. Higher energy losses.	[11], [22], [24],[32]

Ongoing efforts are being made to enhance the efficiency of overhead power transmission lines (OHTL) by incorporating novel materials into conductors, with the goal of reducing Joule losses. One such initiative is the CALAJOULE project, which is co-financed by the Italian Ministry of Economic Development as part of the "Ricerca di Sistema" program. This project aims to propose innovative solutions for overhead line conductors that effectively mitigate Joule power losses. Through this project, an innovative conductor, of which core is made of a carbon fibre composite material is proposed and proved to significantly reduce joule losses of OHTL [16], [20], [21], [53], as shown in Figure 3. This choice allows, with the same breaking load, to have a conductor core of reduced section, with a significant decrease in weight and thermal expansion compared to the traditional conductor (1/10 compared to steel).

By conducting an economic analysis, it was assumed that the conventional ACSR conductors in the current Italian high voltage (HV) and extra-high voltage (EHV) transmission grid would be replaced by the innovative conductors. The findings indicate that this substitution could lead to a significant reduction of 19% in Joule losses. As a result, it is estimated that such a change would generate annual savings of over 2 million Euros, with a total projected savings of more than 37 million Euros over the expected 40-year lifespan of the overhead lines (OHL).

Considering the environmental perspective, assuming an emission rate of 0.39 tons of CO2 per megawatt-hour (t/MWh), replacing the traditional conductor with the innovative one would lead to a significant reduction in carbon dioxide emissions. Specifically, this replacement would result in an annual saving of 21.187 kilotons (kt) of CO2. Over the expected 40-year lifespan of the overhead lines, the total savings would amount to 847.475 kilotons (kt) of CO2.

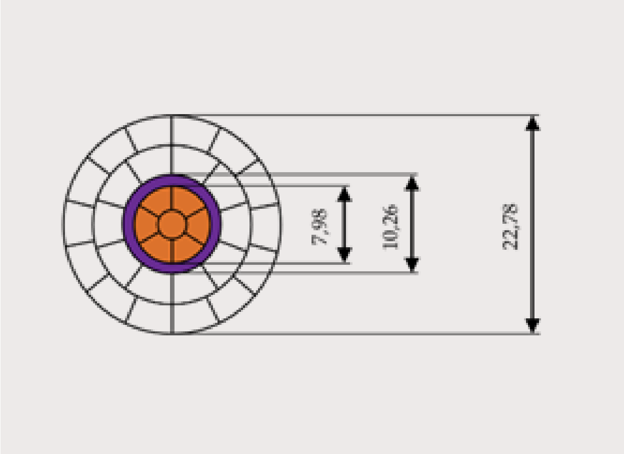

Figure 3 – Section of the ACCM/TW conductor with diameter 22.78 mm [16]

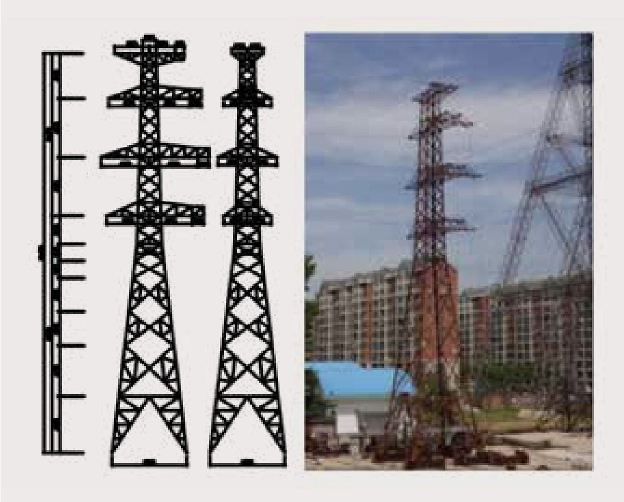

Figure 4 – General map of double circuits 110STJ tower [11]

Structure Heights and Widths

A new tower design for OHAC 110 kV, called 110STJ tower that is of Double circuits and access other lines with single π type, which is used in China for the first time, as presented in Figure 4 [11]. The Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC has designed the double circuits of the 110STJ tower based on the principle of "reducing land area, minimizing obstructions, and preserving the environment" in line with general tower design concepts. The tower features a unique longitudinal arm located at the outer end of the cross arm. This design incorporates insulator strings at both ends of the special longitudinal arm to connect the transmission line leads and facilitate the connection of the new transmission line with a jumping string. The 110STJ tower effectively meets the requirements of practical engineering and serves as a valuable reference for the selection of 110kV tower transmission lines.

Cross-arm

In [23], an innovative insulated cross-arm is proposed, which could help to achieve a compact overhead line operating at 380 kV but having similar height of a 150 kV, Figure 5 and Figure 6 provide a comparison of these two overhead line tower and a detailed structure of the insulated cross-arm configuration. This new line allows for almost 10 times higher transfer capacity of energy. This may be an interesting example for other global utilities experiencing low public support of new overhead lines.

EMF

The assessment of risks of being exposed to electromagnetic field (EMF) under transmission line is important. The directive 2013/35/EC of European Parliament gives definition of the magnetic flux density limit from public health point of view. According to the defined limit, the RMS value of magnetic flux density for low action level, high action level and maximum safe value are 1.13 µT, 6.13 µT and 18.13 µT, respectively. This EMF could be either measured on site or calculated by certain methods.

[4] proposes a computing approach which could be used to determining the magnetic flux density under a transmission line. In this study, the magnetic flux density of a 400 kV OH transmission line is investigated. The 400 kV line parameters are:

- Steel-aluminium conductors with cross-section 500 mms
- Horizontal placement of conductors with a 5.5 m horizontal separation between phases
- Phase conductor suspension 24 m

Three curves are obtained from this computing approach, curve 1 – under tower (H=24 m). curve 2 – under the conductor at a point between them (H=12.75 m), curve 3 – under the conductor sag (H=9 m). As shown in Figure 7, all of them are below the high action level of 6.13 µT and also far less than the maximum safe limit value of 18.13 µT. This gives the confidence that with proper design the magnetic flux density could be reduced to a safe value that is not supposed to cause health issue to public based on relevant standard.

Other aspects

In contrast to HVAC (High Voltage Alternating Current) overhead transmission lines, HVDC overhead transmission lines experience ion flow and space charge, which can exacerbate issues related to contamination and corona. To mitigate these challenges, it is possible to utilize conductors that are coated with an insulation layer for HVDC overhead transmission lines. This approach helps to suppress corona discharge and reduce the effects of contamination. In [10], electric field of HVDC overhead transmission lines with covered conductors are calculated and analysed. A bipolar ±800kV HVDC overhead transmission line is used in the calculation. The height of bipolar ±800kV HVDC transmission lines is 18m. The distance of bipolar conductors is 25m. Four bundled conductors are used. The spacing between sub-conductors is 60cm. Radius of sub-conductors is 2.0975cm. The ion flow field of conductors covered with insulation layers at different thickness is calculated and presented in Figure 8.

Figure 5 – Example of the tower for the compact 380 kV overhead line equipped with insulated cross-arms based on composite insulators (left) in parallel with the existing 150 kV line (right) [23]

Figure 6 – Photo of the insulator set-up for pollution tests [23]

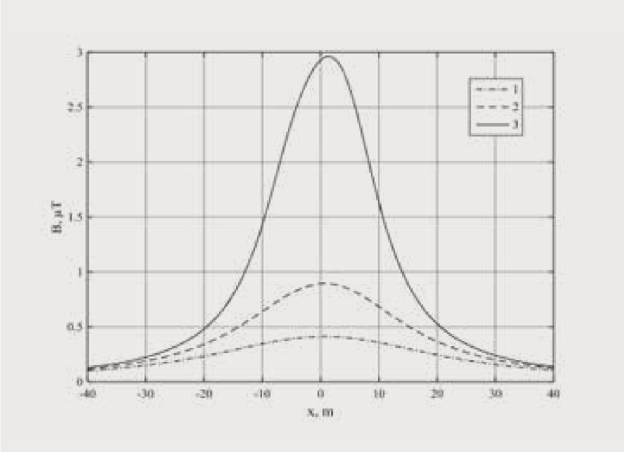

Figure 3 – Section of the ACCM/TW conductor with diameter 22.78 mm [16]

Table 6 – Estimated outage duration for OHLs according to tower type, voltage level and distance from roads [5]

Distance (m)	Estimated outage duration (h)			
	110 kV		330 kV	
	Steel	Concrete	Steel	Concrete
< 100	12	8	16	12
100 -1000	24	12	24	24
1001 -10000	36	24	48	36
> 10000	72	72	72	72

The results show that as the increase of the insulation thickness, the ion flow electric field reduces. It indicates that covered conductors can restrain ion flow field significantly.

4.2.2 Reliability

Outage duration

Duration of the outage is usually determined by the type of failure, complexity and time of repair works of assets. A table illustrates the duration of outage at different voltage levels based on Estonian transmission system operators is presented in Table 6 [5]. The longer the distance from roads, the longer is the outage. Concrete tower tends to have less outage duration compared to steel tower type. Also, higher voltage level in many cases have longer outage duration.

4.2.4 Operating and Maintenance requirements

Hybrid HVAC/HVDC has various AC/DC interaction phenomena. In [12], the AC impact on the DC power circuits switched off for maintenance purposes was studied. The findings indicate that transposing the AC power circuits of the hybrid AC/DC transmission line is an effective approach to reduce induced currents in the de-energized DC conductors. However, it is important to note that AC line transposition can lead to a substantial increase in touch voltages on the de-energized DC conductors. This increase in touch voltages can potentially result in violations of safety regulations or standards.

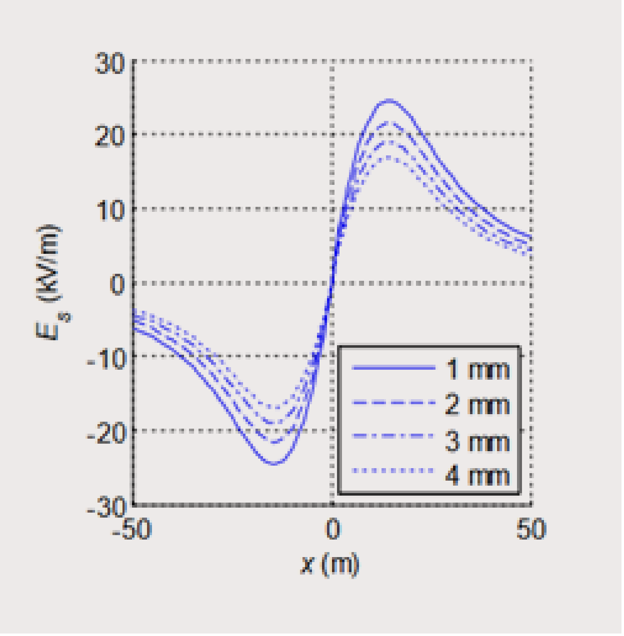

Figure 8 – Electric field at surface of the ground under HVDC overhead transmission lines based on ion flow field calculation with the thickness of insulation layer being 1, 2, 3 and 4 mm, respectively [10]

4.2 Economic aspect

4.2.1 Project Planning and Pre-Design

Economic comparison of HVAC and HVDC – Egyptian case study

To achieve the government's objectives of reducing global warming by 2030, wind farms are being considered as a crucial solution. In Egypt, the planned target is to have more than 7000 MW of wind power capacity by 2022, with 4000 MW planned to be generated by wind farms in the Suez Gulf region. In this context, HVDC (High Voltage Direct Current) technology, based on either VSC (Voltage Source Converter) or LCC (Line Commutated Converter), emerges as a viable alternative to HVAC (High Voltage Alternating Current) systems for integrating wind farms into the power grids. HVDC technology offers several advantages for the efficient transmission of power from wind farms to the grid. In [24], three transmission system configurations are considered to transmit the targeted power of 4000 MW 75 km from the wind farms in Suez Gulf to the national grid, they are:

- 500 kV new HVAC system with underground cable.
- ±320 kV new HVDC system with underground cable.
- ±160 kV HVDC system based on the existing 220 kV OHL.

A comparison of the estimated cost of these three alternatives could be seen from Table 7. The comparison reveals that HVAC (High Voltage Alternating Current) underground cables and HVDC (High Voltage Direct Current) underground cables are costlier compared to HVDC overhead lines (OHL). The primary reason for this cost difference is that the HVDC OHL alternative utilizes the existing 220 kV OHL infrastructure, resulting in significant savings by avoiding the construction of new transmission lines and towers, although infrastructure upgrades may still be required. The cost per kilometer data demonstrates that HVDC OHL is the most economical option at 12 million Euros per kilometer, followed by 500 kV HVAC underground cable at 19.76 million Euros per kilometer, while the most expensive option is the ±320 kV HVDC underground cable at 26.63 million Euros per kilometer.

Table 7 – Cost estimation for the proposed 74 km transmission systems between Ain Sokhna and Zafarana "cost in M$" [24]

No	Item	HVAC 500kV cable	HVDC ±320kV cable	HVDC ±160kV OHL
1	Substation 4000MW	282.87	800	800
2	4000MW TL	1118	1077	-
3	STATCOM		-	-
Invest. fixed cost		1400.87	1877	800
4	Variable cost	81	100	100
Total cost		1481.87	1977	900
5	cost/ km	19.76	26.63	12
PTC		4940 $/MW.km	6590 $/MW.km	3000 $/MW.km

Economic comparison of HVDC cable and HVDC OHTL

A global perspective for developed and developing countries in the HVDC projects by year, voltage, power, distance, type, and supplier is shown in Table 8 [15]. In a case study in Turkey, the cost input in the HVDC project is shown in these tables below. The total cost of HVDC-500 kV, underground cable/OHTL is illustrated in Table 9. It can be observed that the ratio of HVDC cable to HVDC OHTL is about 5.5.

Table 8 – The HVDC projects in several countries [15]

Name of the Project	Country	Year	Voltage (kV)	Power (MW)	Distance (km)	Type	Supplier
Three Gorges-Shanghai	China	2006	500	3000	1060	Thy	ABB
Estiink	Estonia-Finland	2006	150	350	105	IGB	ABB
NorNed	Netherland -Norway	2008	450	700	580	Thy	ABB
Yunnan-Guangdong	China	2010	800	5000	1418	Thy	Siemens
SAPEI	Italy	2011	500	1000	435	Thy	ABB
BorWin1	Germany	2012	150	400	200	IGB	ABB
Mundra-Haryana	India	2012	500	2500	960	Thy	Siemens
Zhoushan	China	2014	200	400	134	IGB	NA
AL-link	Aland-Finland	2015	80	10	158	IGB	ABB
Western Alberta TL	Canada	2015	500	1000	350	Thy	NA
Nord: Balt	Sweden Lithuania	2015	300	700	450	IGB	ABB
Skagerrak 4	Denmark Norway	2015	300	700	244	IGB	Nexans, ABB
Jinsha River II-East China	China	2016	800	6400	NA	Thy	NA
DolWin2	Germany	2016	320	900	135	IGB	ABB
SydVastlanken	Sweden	2016	300	720	260	IGB	Alstom
Western HVDC Link	UK	2017	600	2200	422	Thy	Prysmain Group, Siemens
Xinjiang-Anhui	China	2017	1100	10000	3333	Thy	NA

Table 9 – Overall investment costs for a case study [15]

	VSC-HVDC (M€)		HVAC-OHTL (M€)	LCC-HVDC- 500 kV (M€)	
	Cable	OHTL		Cable	OHTL
Station	153	153	39,7	120	120
Transmission	2400	340	700	2400	340
Compensation	-	-	40	-	-
Total Cost	2553	493	769,7	2520	460

Economic study of uprate OHTL by replacing ACSR conductor with HTLS conductor

One way to increase the power transfer capacity is to uprate the OHTL by replacing ACSR conductors with HTLS conductors. In [17], a study in cost evaluation of current uprating of overhead transmission lines using ACSR and HTLS conductors based on a 230-kV, double-circuit, single-bundle, overhead transmission line in Thailand is conducted. One ACSR and five HTLS with comparable sizes are selected for this study.

The total costs of current uprating are divided into five cost components:

- construction & installation costs
- conductor cost
- cost of energy losses
- land cost.
- demolition cost

Details of cost comparison in different uprating scenarios could be found the [17]. To conclude, it is suggested to consider the option of replacing ACSR conductor with HTLS conductor. It was found that cost of energy losses is the most important cost component, especially when the line is heavily loaded.

Economic comparison of three and four-conductor bundled 380 kV OHLs

An economic comparison between three and four-conductor bundled 380 kV OHLs was conducted in [26], the results show that the advantage offered by the four-conductor bundled solution depends strongly on the length of the line and on the load power factor. To be more specific, the addition of a fourth conductor per phase in transmission lines can theoretically enhance the transmission capacity by approximately 33%. However, this increase in capacity is applicable only for limited line lengths, typically ranging from around 50 to 100 kilometers. Beyond these distances, the benefits of adding a fourth conductor diminish, and alternative strategies may need to be considered to achieve higher transmission capacities.

The economic comparison, considering capitalized costs, emphasizes the advantage of utilizing a four-conductor bundled solution, particularly for heavily loaded transmission lines. This is primarily due to the significant impact of actual Joule losses on the overall costs. In such cases, the reduction in Joule losses achieved through the four-conductor bundled configuration outweighs the other associated costs, making it a more favourable and cost-effective option.

Maintenance cost

The factors which impact the O&M costs are age of the line, weather conditions and length of the line. In [19], the O&M costs are assumed as 1.5% and 0.15% of capital investment cost for OHTL and UGTL respectively.

In [18], a D-distance risk factor was proposed to prioritize high-voltage transmission lines from high to low risk in transmission line maintenance and renovation management in Thailand. Based on this study results, the maintenance cost at 115, 230 and 500 kV could be summarised as shown in the table below. As can be calculated from Table 10, the ratios of the total maintenance cost of 115kV, 230kV and 500kV are 1:1.24:2.52.

Table 10 – Maintenance cost of 115, 230 and 500 kV HVTL (KTHB/km) [18]

Group	115 kV		230 kV		500 kV	
	EQC	MC	EQC	MC	EQC	MC
conductor	508	43	900	50	1500	100
conductor accessory	66	35	67.5	40	120	70
insulator	50.18	130	72	150	100	200
steel structure	1600	100	1800	114	2600	2300
foundation	600	95	750	100	1000	200
lightning protection	130	35	150	40	300	100
tower accessory	4.8	4.8	5	5	10	10
right-of-way	15	15	18	18	25	25
sum	2973.48	457.8	3762.5	517	5655	3005
total maintenance cost (EQC + MC)	3431.28		4279.5		8660	
HVTL Information	115 kV		230 kV		500 kV	
investment of new line (THB/km)	3508.28		4285.06		10949.71	
ACSR conductor, double circuit	2 x 795 MCM		2 x 1272 MCM		4 x 1272 MCM	
inflation rate: IR (%)	3		3		3	
demand of sale: DS (MW)	100		100		100	
down time DT (hrs)	3		4		5	
electricity rate: ER (THB/kWh)	2.977		2.513		2.479	
loss of penalty fee: (LPF (THB/kW)	0.5		0.7		0.9	

Lifecycle cost

Transmission utilities in the recent years are drawing greater attention towards performing life cycle costing studies for cost management and decision making. Net present value is a way to perform life-cycle cost analysis.

Based on net present value method, in [19], life-cycle cost analysis is conducted for a range of transmission lines in India. Based on observations, it has been determined that the life cycle cost of a 220kV overhead transmission line (OHTL) is approximately 65% higher compared to a 132 kV OHTL, despite providing nearly 2.5 times more power carrying capacity. Similarly, the life cycle cost of a 400 kV OHTL is found to be 56% and 85% higher, respectively, in comparison to 220 kV and 132 kV OHTLs, while providing 3.5 and 8.5 times more power carrying capacity. These findings highlight that higher voltage OHTLs offer significantly increased power carrying capacity but also come with higher life cycle costs.

Furthermore, it has been observed that the life cycle costs of underground transmission lines (UGTL) are significantly higher compared to overhead lines, primarily due to the high capital costs associated with underground installations. Specifically, the life cycle cost of a 220 kV UGTL is approximately 19% higher than that of a 132 kV UGTL, despite being capable of carrying 2.5 times more power. Similarly, the life cycle cost of a 400 kV UGTL is found to be 14% and 31% higher, respectively, compared to 220 kV and 132 kV UGTLs, while providing 3 and 7 times more power carrying capacity. These observations highlight the considerable cost disparity between underground and overhead lines, with underground options incurring significantly higher life cycle costs. Overall, the life cycle costs of UGTL are two to six times more than OHTL [19].

In the breakeven analysis, the point at which the investment for overhead transmission lines (OHTL) and underground transmission lines (UGTL) becomes equal is determined. However, a forward breakeven analysis procedure cannot be straightforward applied to compare OHTL and UGTL due to the substantial and exponentially increasing difference in capital costs over the useful life of both types of lines. Instead, an alternative approach involves determining the breakeven point by considering the cost of land as a reference for the construction of these lines. This approach helps in understanding the point at which the costs of OHTL and UGTL converge and become comparable. Figure 9 presents a comparison of OHTL and UGTL overall cost per km as a function of cost of land for 400 kV. Table 11 summarises the breakeven for different voltage levels.

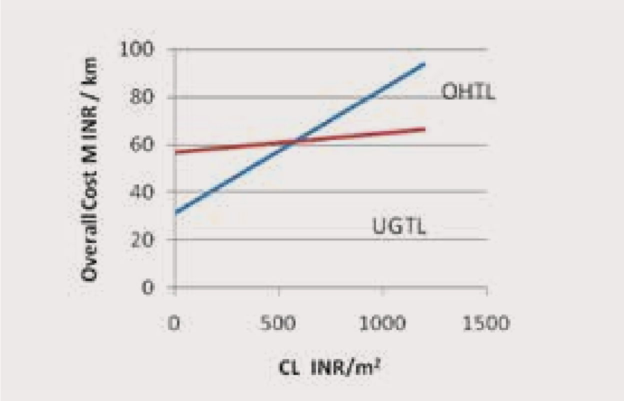

Figure 9 – Overall cost per km as function of CL for 400 kV lines [19]

Table 11 – Results of breakeven analysis [19]

Voltage Level (kV)	Breakeven Cost (INR/m^2)		
		Uncertainties case	
	Base Cable	Lower Bound	Upper Bound
132	1200	1250	1450
220	900	820	1070
400	550	450	650

4.3 Hybrid AC/DC

Given the time, investment, and public acceptance required for the construction of new overhead lines, the conversion or modification of existing AC corridors into hybrid AC/DC lines presents an intriguing solution. This approach allows for the transmission of bulk power from renewable energy sources (RES) and addresses local bottlenecks while minimizing the need for significant new investments. Additionally, it helps mitigate risks associated with objections and delays that often accompany the construction of entirely new transmission infrastructure. By leveraging existing AC corridors and integrating DC transmission, this hybrid solution offers a more efficient and cost-effective means of expanding transmission capacity and supporting the integration of renewable energy into the grid [14]. Research focused on the feasibility of integrating AC and DC technologies within the same infrastructure has been undertaken with the aim of converting AC circuits into DC circuits. The objective is to explore the potential for combining both AC and DC transmission systems in a coordinated manner, leveraging existing infrastructure while reaping the benefits of DC technology. This research aims to assess the technical and economic viability of such hybrid systems, considering factors such as compatibility, efficiency, grid stability, and the overall cost-effectiveness of the proposed integration. By sharing the same infrastructure, this approach has the potential to optimize resource utilization and enhance the flexibility of the power grid.

In [14], one proposal is presented to take advantage of selected existing AC transmission corridors and increase their power transfer capacity by its transformation onto AC/DC corridors. Figure 10 shows the superimposed-line strategy for European network, which consists OF interconnecting the most distant regions by adjusting selected existing HVAC lines to add new HVDC corridors. The idea is to benefit from the existing right-of-way of lines by adding new conductors to existing transmission towers, as illustrated in Figure 11.

Economical estimates could be conducted to identify the cost range of upgrading existing AC to hybrid AC/DC. Table 12 presents the derived for different transmission capacity upgrading alternatives. The cost categories suggested are: a) converter costs; b) land use; c) line costs and d) right of way.

The estimated converter costs in this analysis assume the use of LCC (Line Commutated Converter) technology, which results in a cost that is 50% higher for VSC (Voltage Source Converter) cases. Both the AC/DC conversion and the proposed hybrid design with an additional DC circuit would have similar cost requirements. In terms of line costs, the reference is based on estimations for a new 2000 MW HVDC bipolar overhead line (OHL). The equivalent AC/DC conversion option would not necessitate new tower installations but would involve the replacement costs of the conversion equipment and tower modifications. On the other hand, the proposed hybrid design does not require new tower installations either but will require more extensive tower modifications compared to a regular AC/DC conversion of a circuit.

The major factors influencing costs in this context are land acquisition and preparation, including the necessary permits. These costs are significantly reduced in the case of the proposed hybrid design compared to a completely new installation. Another significant cost factor is tower design and modifications. In the case of the hybrid design, these costs are expected to be slightly higher than the estimates for AC/DC conversion due to the additional circuit requirements. However, it is important to note that the overall impact of these costs will depend on the specific project and its unique circumstances.

Based on this comparison, the proposed hybrid design would achieve to cost between 0.3 and 0.8 M€/km. Also, a comparison of the proposal with the installation of new HVDC OHL, following similar routes and excluding land acquisition costs, results in almost 20 percent of savings as shown in Table 13.

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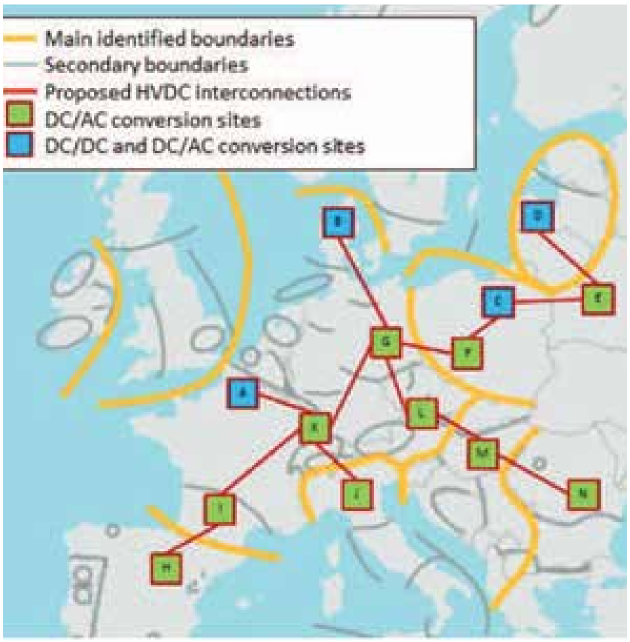


Figure 10 – A possible hybrid AC/DC transmission network proposal [14]

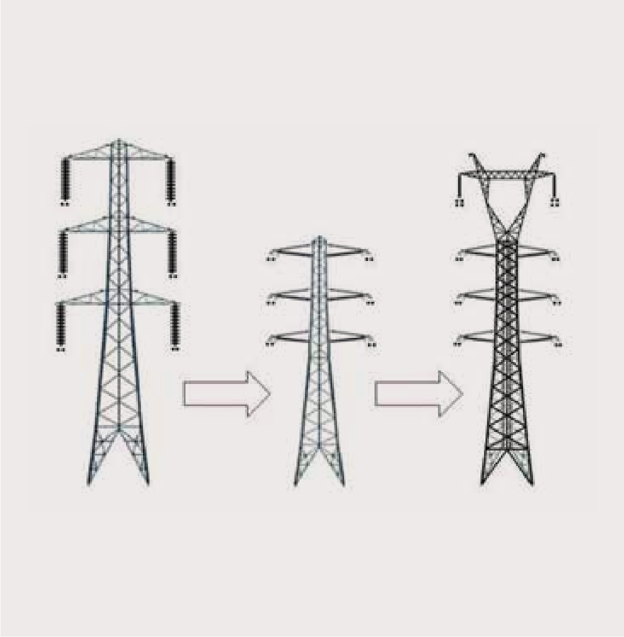


Figure 11 – A possible upgrading proposal of a typical transmission line design to a compact tower with composite arms and additional module (not to be considered as a final design) [14]

The major factors influencing costs in this context are land acquisition and preparation, including the necessary permits. These costs are significantly reduced in the case of the proposed hybrid design compared to a completely new installation. Another significant cost factor is tower design and modifications. In the case of the hybrid design, these costs are expected to be slightly higher than the estimates for AC/DC conversion due to the additional circuit requirements. However, it is important to note that the overall impact of these costs will depend on the specific project and its unique circumstances.

Based on this comparison, the proposed hybrid design would achieve to cost between 0.3 and 0.8 M€/km. Also, a comparison of the proposal with the installation of new HVDC OHL, following similar routes and excluding land acquisition costs, results in almost 20 percent of savings as shown in Table 13.

Table 12 – Related costs comparison for upgrading transmission capacities technologies for OHL [14]

Category	Upgrade Technology		
	New line	AC/DC conversion	Proposal
a (USD/unity)	300000 [a]	same	same
b	yes	moderate	moderate
c (USD/km)	250000	less + AC removal	less
d	yes	N/A	N/A
a 50% higher for VSC			

Table 13 – Comparison of total line costs of the proposal vs. new corridor installation [14]

Scenario	New HVDC OHL (M€)	Proposal (M€)	Savings (%)
1	35915	29000	19
2	57670	46485	19

4.4 HVDC

HVDC technology has been in mainstream use in power systems for over 50 years and is now well matured, with over 100 schemes in service worldwide, and this number continues to grow. The thyristor has been the exclusive semiconductor in use for most of this period, with an LCC HVDC link rating of ±500kV, 3000MW as the common industry maximum [22]. In recent years there have been significant advances in 2 directions:

- Extending the LCC rating up through ±600kV, ±660kV and ±800kV, with planned development up to ±1100kVdc for China.
- Introducing VSC HVDC on a large scale, with ratings up to ±320kV, 1000MW, and increasing still further as investment in development continues to take advantage of new semiconductors.

Indeed, the new Voltage Source Converter (VSC) technology has brought about a more robust solution to the complexity of multi-terminal High Voltage Direct Current (HVDC) systems. This technology has become the focal point of national, regional, and even continental scale grid developments worldwide, where HVDC is being extensively deployed. The advantages of VSC-based HVDC systems include improved control capabilities, enhanced grid stability, better utilization of renewable energy sources, and the ability to connect multiple terminals or grids together. This technology has opened up new possibilities for large-scale grid integration, enabling the transmission of power over long distances with reduced losses and improved efficiency. As a result, VSC-based HVDC systems are being increasingly adopted in grid expansion projects globally, as they provide a reliable and flexible solution to meet the growing demands of modern power systems.

Presently available LCC and VSC technology mainly consists of:

- HVDC circuit configurations
- Main circuit components and equipment
- Station Layouts

For HVDC circuit configurations, HVDC interconnections may be configured in a number of different forms, namely:

- Back to Back
- Cable Transmission
- Line Transmission
- Multi-terminal

For line commutated converters, the main power circuit of an LCC HVDC converter station consists of the following major areas and equipment:

- Thyristor Valves
- Converter Transformers
- AC Harmonic Filters
- AC Switchyard
- DC Smoothing Reactor
- DC Harmonic Filters
- DC Switchyard

Figure 12 shows typical layouts for LCC converter stations, noting that the dominant area of the footprint is the AC switchyard and the AC Harmonic Filters.

For voltage source converters, the main components in the power circuit of a VSC HVDC system are as follows:

- IGBT Converters
- Converter Transformers
- Arm/Limb Reactors

Figure 13 presents the layouts for VSC converter stations. In VSC layouts, the main difference between these and LCC is the absence of AC harmonic filters.

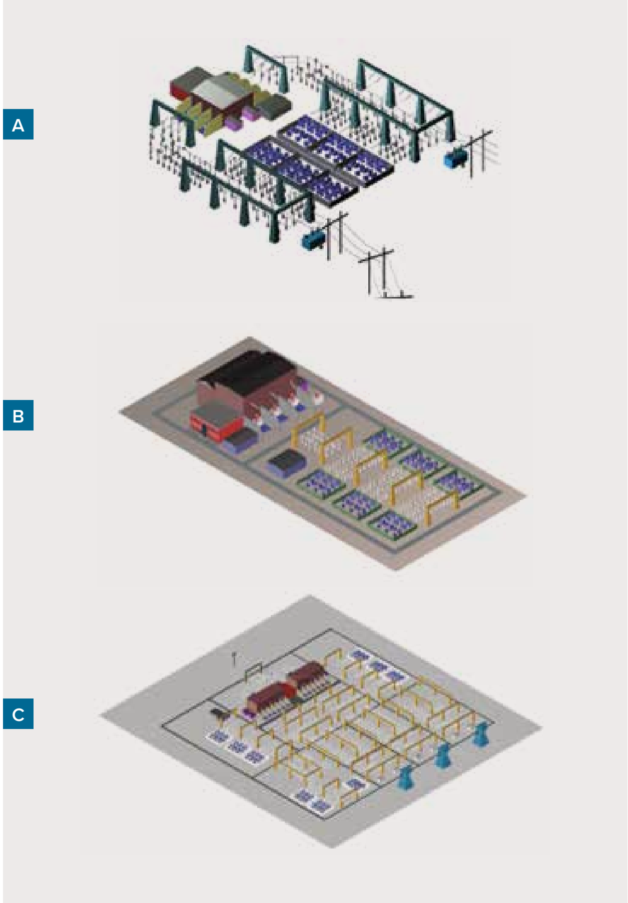


Figure 12 – Typical layouts for LCC converter stations: (a) back to back monopole HVDC converter station; (b) HVDC monopole cable converter station; (c) HVDC bipole overhead line converter station [22]

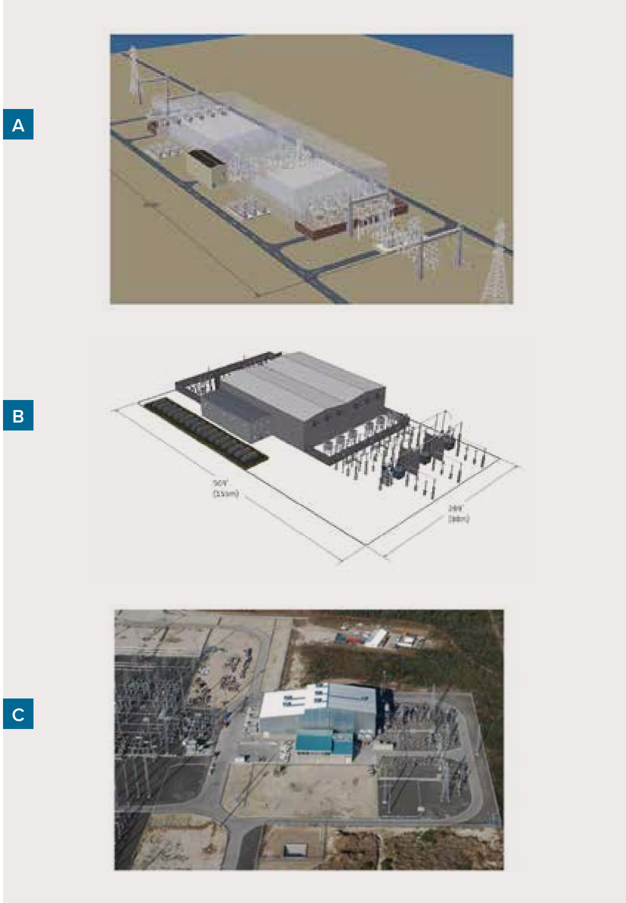


Figure 13 - Typical layouts for VSC converter stations: (a) back to back VSC HVDC converter station; (b) VSC cable converter station; (c) Overhead line VSC HVDC converter station (courtesy ABB) [22]

5.

Discussion (UG cables)

5.1 Technical aspects

It should be noted that the literature research on underground cable mainly focussed on recent research papers which are Significant or Relevant Research Material (SRM) including following three Key research materials from grey literature:

- EPRI Underground Transmission Systems Reference Book 2015 "Green Book" [27]
- CIGRE report "Implementation of long AC HV and EHV cable system" Working group B1.47 dated March 2017 [2]
- CIGRE 2006 paper B1-305 "A dynamic rating system for an existing 150 kV power connection consisting of an overhead line and undergroundpower cable" [3].

5.1.1 Design aspects

Power Transfer Capability

The OHL current rating is based on conductor properties and static environmental conditions (temperature, wind speed and sun radiation). If the same conductor is used for an underground cable, it will have a lower current rating because heat from buried cables must pass through the earth before reaching the air which is the ultimate heat sink [2], [27]. Also, the cable's coaxial electrodes and outer shielding create a capacitance that affects power transfer. Moreover, the dielectric losses in cable insulation are present any time the cable is energized and reduces the amount of power transfer [27]. Therefore, the cable might require two cables per phase (essentially two cable systems) to match the capacity of the overhead line [3], [27]. The current rating can be increased by the conductor size and conductivity (copper instead of aluminium) [2]. Figure 14 shows the variation in rating versus conductor size. It is worth to note that with two cables per phase, the per-cable rating with two cables/phase is approximately 88% (not 100%) of the single-cable rating [31]. However, larger cross sections or numbers of cables per phase for UG cables can be economically unattractive [3], [28].

In many circumstances the thermal inertia of underground cables should be considered when matching a cable to an OHL. This can result in smaller conductor sizes, cheaper conductor materials, less cables per phase and hence a reduced installation trench width. A reduced installation swath not only reduces civil costs but may ease right of way requirements and allow the cable system to be installed in narrow installation corridors. Reducing the number of cables per phase also give less maintenance and especially for high voltage cables it produces less reactive power.

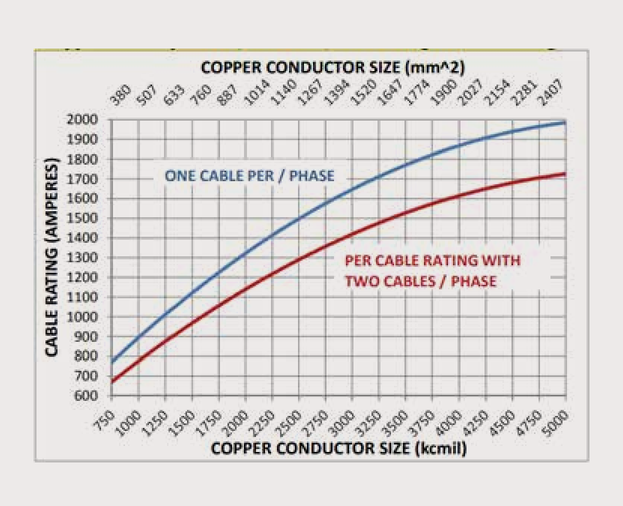


Figure 14 - Variation of cable current rating with cable size [31]

The selection of circuit types used in UG cable is shown in Figure 15. Figure shows duct-manhole and pipe system which have advantages in cities of fast installation and less disruption to traffic [27]. Direct buried systems have higher ampacities. Tunnel systems have more direct routes and good protection from third party disturbance. Figure 15 also shows DC transmission circuits require two parallel cables while AC transmission circuits require three cables. For comparison purpose the cables in Figure 15 are shown installed at a common minimum depth. It is usual to specify a minimum depth of burial to the top of the cable for rural and urban sections of the route. Depth provides increased protection from dig-in and plow damage. Increased depth also decreases the magnetic field at the surface [27].

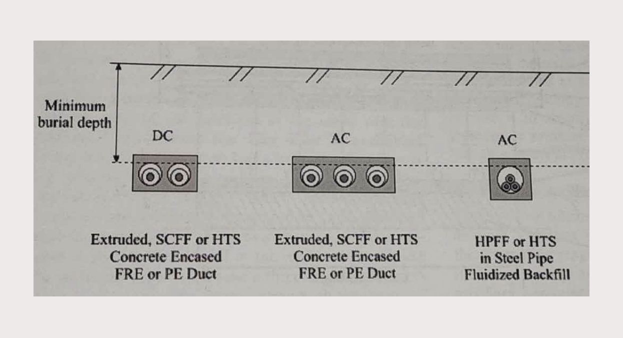


Figure 15 Underground cable circuit cross section for ac and dc transmission[27]

Four cable systems that can be considered for underground installations are following [27]:

- Extruded dielectric with XLPE or EPR insulation
- Self-contained fluid filled (SCFF) or gas filled (SCGF) cable
- Pipe type, either fluid filled, or gas filled
- Special (Gas insulated lines)

This report mainly discusses the Extruded with XLPE cable and pipe type cables. Gas insulated lines are not discussed in this report because that is out of scope of the literature review.

Pipe type cables have been the most commonly used cable system at higher voltages. Now, with the advances in purity of extruded dielectric cables, they are becoming more common at increasingly higher voltage levels and longer circuit lengths [27].

XLPE insulated cables are being designed and installed at voltages up to 230 kV and 345 kV in long lengths. Over the past 20 years, there has been significant and swift progress in the advancement of high-voltage (HV) and extra-high-voltage (EHV) cables that utilize Cross-linked polyethylene (XLPE) as the insulating material. For instance, contemporary XLPE cables possess improved characteristics such as a reduced dielectric constant and the ability to operate at higher temperatures, making them significantly more effective compared to the older paper-insulated cables that were impregnated with oil [2]. Also, the simplified manufacturing process of XLPE cables has resulted in a remarkable surge in the availability and utilization of HV AC cables. For example, in China, more than 1100km of 220 kV and 100km of 500 kV cable were produced in China in year 2014 and during the past 10-15 years more than 100,000km of HV & EHV cables have been installed in the country [2]. Currently worldwide more than ten fully qualified manufacturers of XLPE insulated AC cable rated at 500 kV are present [2].

SCFF cables are generally only used in specialized extra high voltage applications.

In urban environments, extruded dielectric cables installed in duct banks and pipe types of cables are frequently used because of their ruggedness and the ability to install short lengths of pipe or ducts at one time in city streets with trench openings of only 300-600 ft. The cable is installed in a separate operation, with minimum traffic disruption [27].

In suburban places, extruded dielectric, pipe type and SCFF cables can be used, depending upon the specific application [27].

In rural areas, any cable system can be suited. Low traffic volume and long trench openings allow flexibility for the designer to consider all different types of cable systems [27].

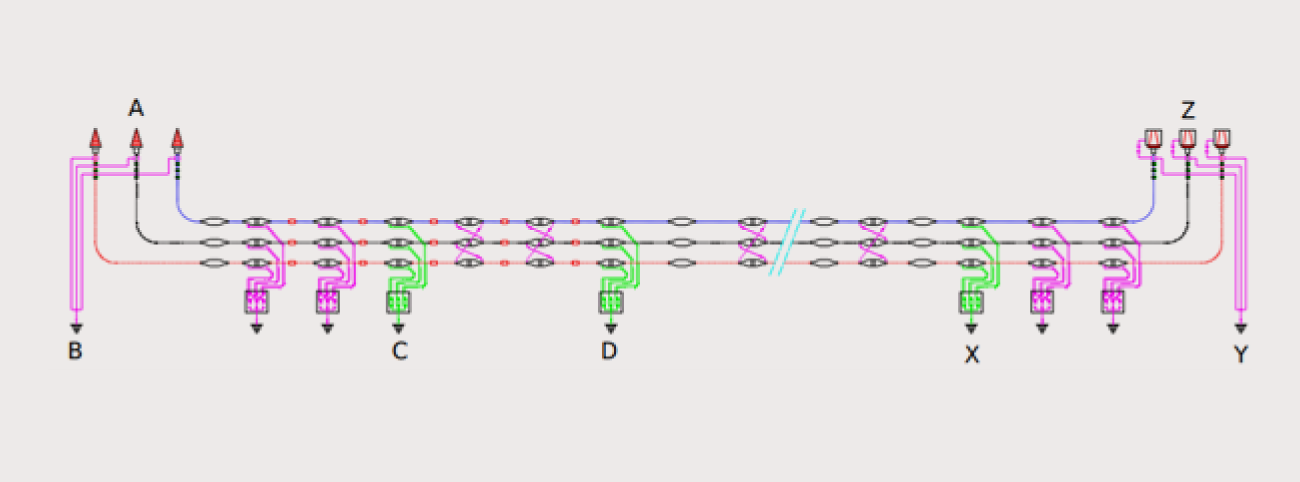


Figure 16 Schematic diagram of extra-long 225kV cable line with direct cross-bonding sections [32]

For special applications such as long underwater crossings, usually SCFF or extruded dielectric cables are used primarily because it is difficult to make pipe type splices underwater. SCFF or extruded dielectric cables are preferred for bridge crossings because the weight and expansion characteristics of pipe type cable requires resolution of bending forces which complicates the design. Also, pipe type cable systems are not economical for short length applications [27].

A practical experience with the newest bonding system called "direct cross bonding" implemented on an extra-long cable system of 2000mm^2 and 2500 mm^2 Cu XLPE 225kV cables, as shown in Figure 16, is presented in [32]. Three different types of joints and their associated hardware are incorporated in this [32].

- Joints with earthing in C, D and X.
- Joints with classical cross-bonding connections between B and C and between X and Y: the screen interruption is protected with SVL's.
- Joints with direct cross-bonding connections on a major part of the line between C and D and up to X: no SVL are provided for the protection of screen interruption against overvoltage.
- Joints without earthing: on some sections, normal straight joint without earthing has been implanted in order to optimize the earthing scheme.

HVDC

High voltage DC (HVDC) transmission cable systems have the potential to transform major electrical grids; they can deliver very high powers over long distances with high efficiency and reliability [41]. As compared to HVAC cables, in HVDC cables the skin effect and the proximity effect in the conductor are absent (so that the section of the conductor is fully exploited). Also, dielectric losses are also absent in practice if leakage currents can be neglected, as is mostly the case. The average higher electric field stress of HVDC cables leads also to a higher utilization of the cable [41]. Moreover, the lower line costs with the same transmitted power. HVDC cable lengths are not limited by charging currents and no reactive compensation (for the cable itself) is required at the end stations and/or at intermediate points as in the case of AC transmission systems [32]. The advantages of HVDC cable over HVAC cable are shown through Figure 17 [28]. A very thorough comparison between the HVAC and HVDC system is presented in [51].

Conductors

The UG cable are typically single-core cable or three core cable with each core consisting of either copper or aluminium conductors. The new underground long length AC cable links are being supplied with single core XLPE cables while the three-core cable is typically used in submarine cables [2]. Although copper conductors are more expensive, they offer lower electrical resistance, allowing for a reduced cross-section and less material for the outer layers. Therefore, wherever there is very high current carrying capacity is required, copper conductors are specified. Additionally, copper was often favoured due to its superior corrosion resistance properties, particularly in submarine cables. However, this consideration is not highly relevant since well-designed cable conductors are designed to avoid contact with seawater. Therefore, aluminium conductors

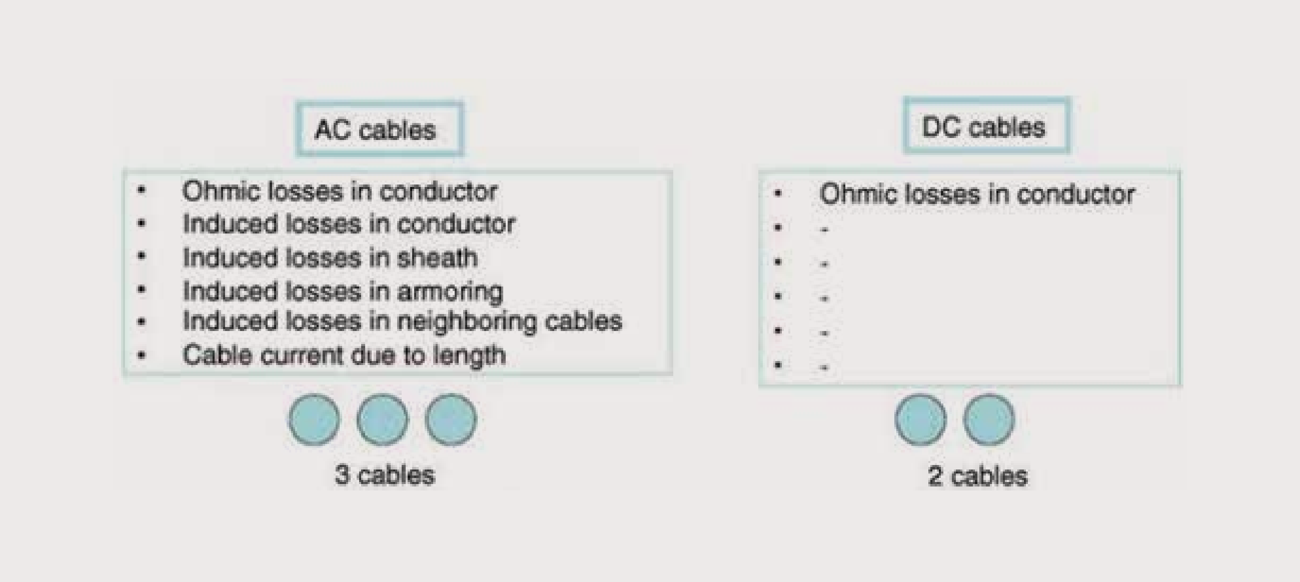


Figure 17 Comparison of HVDC and HVDC cable [28]

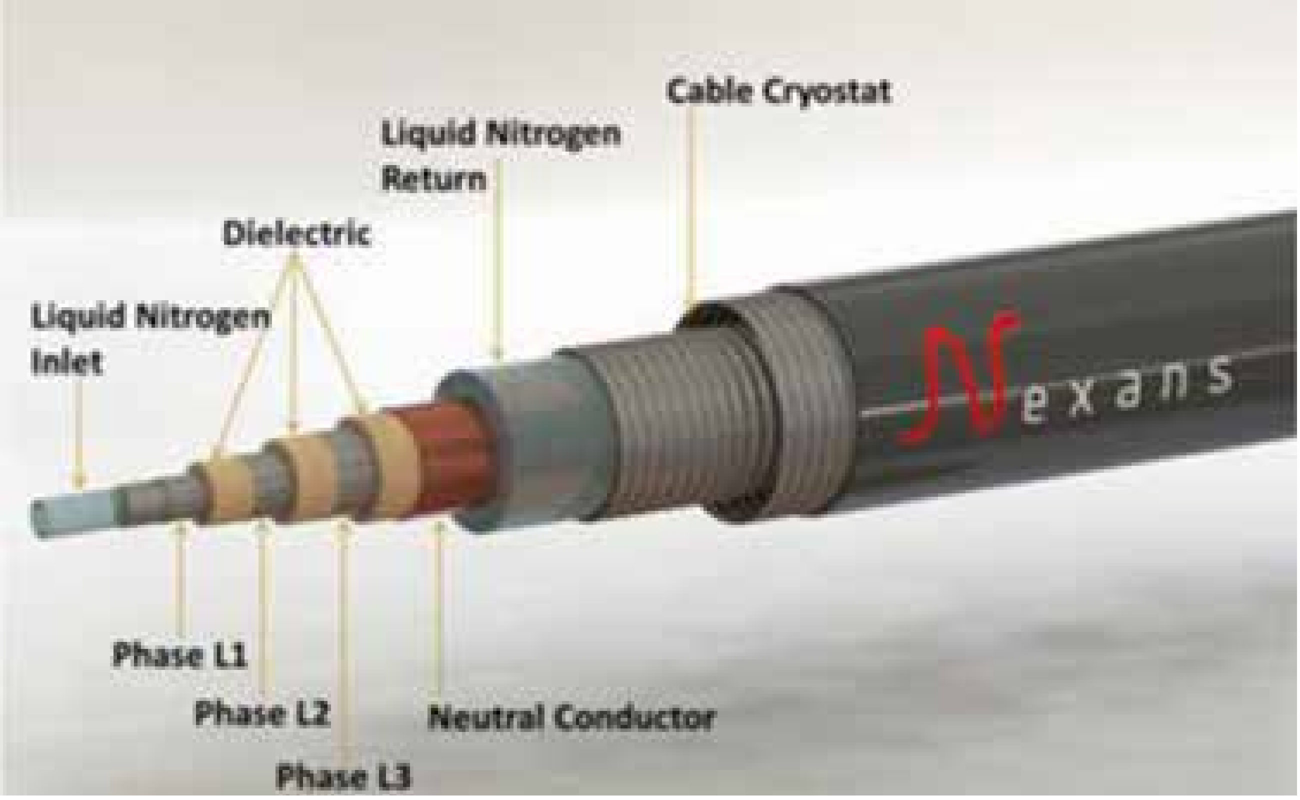


Figure 18 Design of a high temperature superconducting (HTS) cable for AC operation [52]

are now gaining broader acceptance due to their lower cost, lighter weight, and better strength-to-weight ratio in mechanical properties. This is particularly notable in deep installation and dynamic situations [2].

Another option with high power transfer capability over long distances are the superconducting cables [49], [52]. The high temperature superconductor (HTS) transmission cables can play a role in strengthening the grid. The advantages as compared to the OH lines and UG cables are: economic, underground, higher power capacity, lower losses, reduced magnetic field emissions in (existing) OHL, compact: less occupation of land and less permits needed, a possibility to keep 380 kV voltage level in the grid for as long as needed [47]. However, a cryogenic envelope is needed to keep the superconductor cooled below its critical temperature to maintain its non-resistivity. The easy availability and use of liquid nitrogen as a coolant allows the superconducting behavior even at higher temperature (T = 77 K) and also simplifies the design of cryogenic envelope. The design of a high temperature superconducting cable is shown in Figure 18 [52].

The design of the superconducting cable itself also requires substantial engineering for optimum performance (especially for AC operation due to the fast-switching magnetic field). However, these challenges have been already addressed and solutions only need to be adapted to the specific transmission line project [52].

A list of global superconducting projects is presented in Table 14 [52].

Table 14 Global superconducting cable projects [52]

Project	location	Length (m)	Capacity [MVA]	Schedule	Operator
LIPA	long Island/USA	600	574 (138 kV AC, 2.4 kA)	In operation since 2008	LIPA
Ampacity	Essen/Germany	1000	40(10 kV AC, 2.3 kA)	Start of operation 01/2014	RWE
	Amsterdam/NL	6000	250 (50 kV AC)	Proposed	Alliander
St Petersburg Project	St Petersburg/ Russia	2500	50(20 kV D, 2.5 kA)	Start of operation 2015	FGC UES[a]
Ishikari	Ishikari/ Japan	2000	100 (± 10 kV DC, 5 kA)	Start of construction spring 2014	City of Ishikari
	Icheon/ Korea	100	154 (154 kV AC 3.75 kA)	Operating since 11/2013	KEPCO[b]
	Jeju Island/ Korea	1000	154 (154 kV AC 3.75 kA)	Operation 2015	KEPCO
	Jeju Island/ Korea	500	500 (80 kV DC)	Operation 2014	KEPCO
HYDRA	Westchester county/ USA	170	96(13.8 kV AC/4 kA)	Start of construction early 2014	ConEdison
	Yokohama/Japan	250	200 (66 kV AC, 5kA)	Operation stopped December 2013, continuation planned with new high-performance refrigerator 2015	TEPCO[c]
	China	360	13 (1.3 kV DC, 10 kA)	Operating since 2011	IEE CAS[d]
REGf	Chicago/US	5 km	to be specified	Planning since 2014	ComEd[e]
Tres Amigas	New Mexico/US		750/5000	Postponed	Tres Amigas LLC

[a] Federal Grid Company United Energy System
[b] Korea Electric Power Corporation.
[c] Tokyo Electric Power Company.
[d] Institute of Electrical Engineering. Chinese Academy of Sciences.
[e] Commonwealth Edistion.
[f] Resilient Electric Grid

The advantages of superconducting power lines compared to the most modern underground standard HVDC cables (7320 kV XLPE HVDC) are [52]:

1. One of the advantages is the compact size of superconducting cables, requiring only a width of a few 10 cm. This is in stark contrast to a standard HVDC ±320 kV cable installation, which necessitates a 17 m wide trench containing 24 cables to achieve a 10 GW capacity. This width measurement does not include the additional 2.5 m safety area on both sides.
2. There is a potential for significantly reduced land usage, possibly as low as 10% compared to standard HVDC cable installations. The extent of land use reduction depends on factors such as capacity, geographical area (urban or rural), and applicable regulations.
3. Superconducting cable provide an attractive solution for long-distance and high-capacity electric energy transportation. This is particularly relevant because standard conductor cables suffer from significant losses (> 6% per 1000 km at full load for ±320 kV XLPE HVDC cables).
4. By adjusting the nominal current to align with the desired or existing operating voltage, particularly in medium and low voltage grids, it becomes possible to eliminate the need for transformers. This has the advantage of reducing the space occupied and the number of components within the grid system, thereby minimizing the likelihood of technical failures.

5. In hot climates, superconducting cable offer a superior solution due to their vacuum-isolated cryogenic envelope. This envelope acts as a barrier, preventing heat from entering the system and effectively stabilizing the temperature of the superconducting conductor. In contrast, the capacity of standard HVDC cables is diminished by higher soil temperatures.
6. Do not heat the surrounding soil.
7. Much easier use of existing right-of-ways (ROW) to transfer GWs of power.
8. The cryogenic system can store energy by cooling to lower operating temperatures at times of high renewable energy input.

Figure 19 shows the right-of-ways and power transfer capacity comparison between ± 800 kV HVDC OH line, ± 320 kV HVDC XLPE cable, and ± 125 kV HVDC superconducting cable [52].

The primary concern raised by communities opposing the construction of new transmission lines is the visual impact they would have. A single pylon of a ±800 kV 6.4 GW HVDC power line has a height of 50–90 m and the width of the corridor would be estimated around 125 m [52]. Two HVDC lines with a maximum capacity of 10 GW (maximum of 12.8 W) span a width of 245 m. Similarly, towers supporting ±500 kV HVDC transmission lines share comparable dimensions but require wider rights-of-ways due to the lower capacity, which scales with the square of the voltage. The visual impact of such infrastructure is substantial: A structure that is 50 m tall can be visible from a distance of ~ 25 km when observed from sea level. This implies that the construction of an overhead HVDC transmission line has the potential to significantly alter the landscape, impacting an area of 50 km^2 for every kilometer of its length [52].

As per authors of [49], for 380 kV and 6.6 GVA, overhead transmission lines require corridors of 70 m in width, in contrast to less than 7.7 m corridor width necessary for superconducting 380 kV cables.

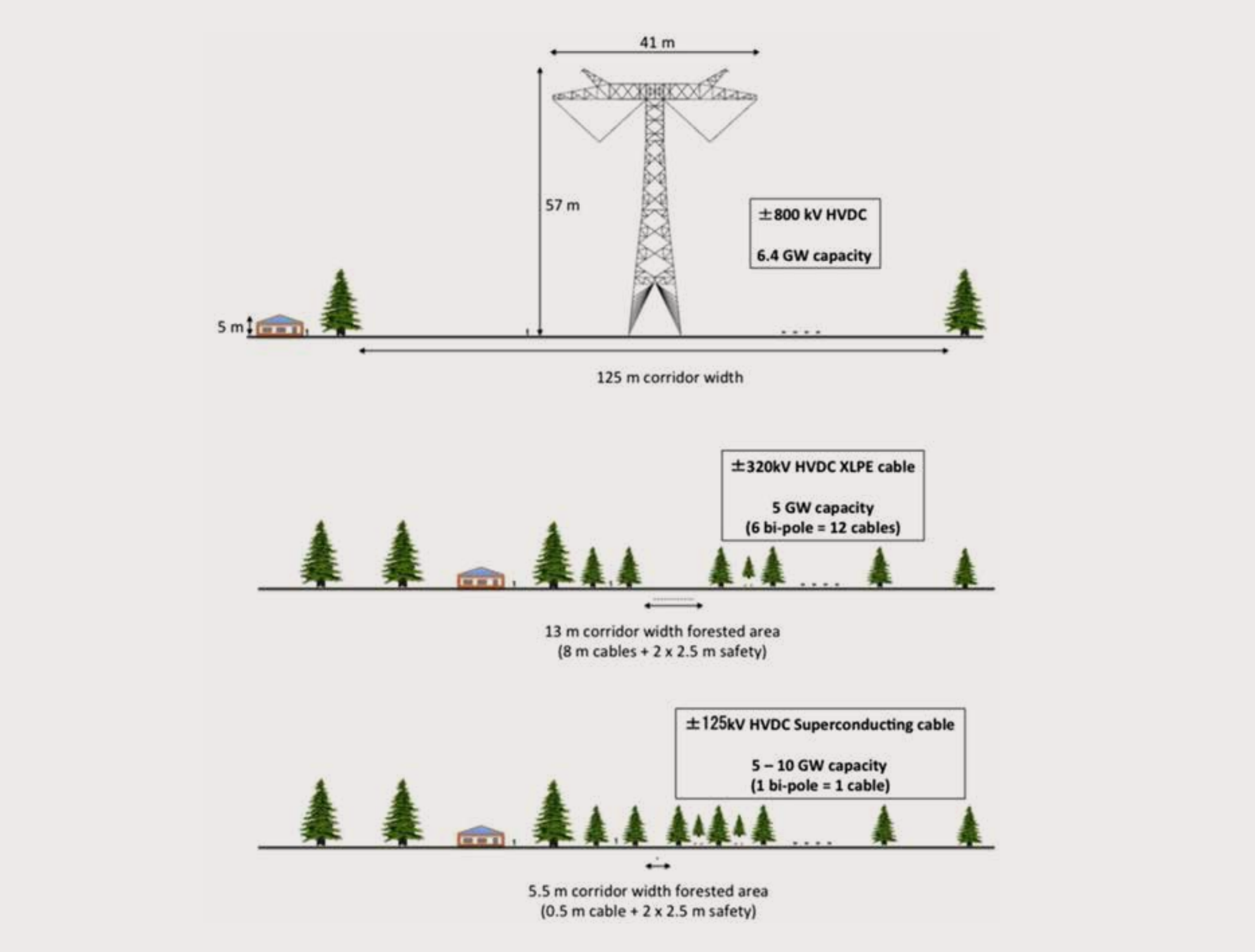


Figure 19 ROW and power transfer capacity comparison between different power transmission lines. [52]

Insulators

XLPE - cross-linked polyethylene which is now one of the most common and well-established insulation materials in modern extruded high voltage cable design. A major reason for the XLPE success is the excellent electrical, mechanical, and thermal properties of the material. The most advantageous features are the low dielectric losses, the low dissipation factor, the high electrical breakdown strength, the high modulus of elasticity and the high tensile strength. Low operating and low maintenance costs, combined with good system availability, results in a low lifetime cost for the XLPE cable system. XLPE is a suitable insulating material for conductor temperatures up to 90 °C which is the normal operating temperature for XLPE cables. The cables can however withstand up to 250 °C under short circuit conditions. Consequently, there is both a high overload potential and a high safety margin in the cables [2].

A HV XLPE Cable with corrugated Aluminium sheath is shown in Figure 20. The cable insulation system is protected from the water by a metallic layer such as lead alloy or a welded metallic sheath which is also used as electrical screen and a PE layer is extruded to protect this metal sheath. The 3 phases are laid up together and optical fibre elements are often laid in the interstices between the cores as well as some other materials e.g. PP ropes or PE profiles. The bundle is then protected against mechanical damage by metallic armour made of steel wires. An outer protective covering is often made of PP yarns applied outside the armouring [2].

The insulation thickness of XLPE cables primarily depends on the required withstand voltage. However, for long-length extra-high-voltage (EHV) cables, the insulation thickness also affects the generation of reactive power by the cable. The below equation indicates that reactive power is primarily influenced by voltage, but also by capacitance and frequency [2].

$$Q\_cable=2\pi fCV^{\wedge 2}$$

where *Q cable* is the reactive power in Var, f is the power frequency in Hz, C is the cable capacitance in farads, and V is the line voltage in volts.

To compensate for reactive power in a system, shunt reactors are commonly installed. However, this solution introduces complexity due to electrical and spatial constraints, increased losses, and the need for redundancy. Therefore, reducing the amount of reactive power produced becomes desirable. This can be achieved by either increasing the insulation thickness or decreasing the conductor size, although the latter is often impractical [2].

Increasing the insulation thickness results in reduced capacitance, leading to lower reactive power compensation, as well as decreased dielectric loss and charging current. However, there are drawbacks to increasing the insulation thickness of XLPE cables. One significant challenge is maintaining the quality of the extrusion process when dealing with very long runs of HV cable. While a small increase in insulation thickness could be beneficial for lengthy EHV cables, it is important to consider the potential negative consequences [2].

Despite these challenges, opting for more insulation in a cable system can yield certain advantages. Some of the additional costs associated with increased insulation can be offset by reduced investments in reactive compensation and lower system losses throughout its lifespan [2].

The HVDC cable insulation system is categorized into two groups: 1) Oil-paper insulation, and 2) Extruded insulation.

Oil-paper insulation: The oil–paper insulation is achieved by wrapping strips of pure cellulose paper onto the conductor, applied in helical layers to reach the total design thickness of the insulation. Then the insulation is impregnated with mixtures or mineral base fluids to impart and improve the dielectric properties. In the polypropylene paper laminated insulation, the traditional paper insulation is replaced with a laminate consisting of alternating layers of paper and polypropylene, thereby improving the characteristics of the dielectric [28].

Extruded insulation: Polymers investigated and tested so far for the construction of extruded insulation HVDC cables can be grouped into two categories: pure materials and materials with proper additives. Cable manufacturers seem to have abandoned the pure

Figure 20 HV XLPE cable [2]

polymeric insulation in favour of insulation with properly selected additives to improve the accumulation of space charges. Extrusion is a technique to deposit a uniform and compact layer of polymer around the conductor, in between the two layers of semiconductive screens [28].

Depending on the type of insulation, different types of cables are designed. The most common typologies of HVDC cables are shown in Figure 21 [28].

Mass-impregnated nondraining (MIND) cables are available for voltages up to 500 kV and a transmission capacity of up to 800 MW in one cable. Oil-filled cables are suitable for DC voltages up to 600 kV DC. Due to the required oil flow along the cable, the transmission line lengths are, however, limited to < 100 Kms. For PPL insulated cables some manufacturers have developed HVDC cable systems with a voltage rating of 600 kV. In extruded HVDC cable, the extruded insulation is polymeric and mostly based on polyethylene compounds, among which the preferred ones are low-density polyethylene (LDPE) and particularly cross-linked polyethylene (XLPE) which is a special kind for best performance under HVDC condition. This special kind of XLPE is commonly referred to as DC-XLPE [28].

5.1.2 Reliability

While overhead lines are generally more susceptible to failures caused by weather conditions, cables tend to have fewer failures. However, in the event of a failure, the time required for restoration can be significantly longer for cables, ranging from days to weeks, whereas overhead lines can be restored within hours to days [31]. If a failure occurs and is limited to a specific set of cables, it is possible to employ certain measures to isolate the failed cable and partially restore power transfer through the remaining circuit. This typically involves using two smaller cables instead of a single cable per phase, which necessitates double the number of terminations and, if needed, splices [31]. An alternative cable system can improve the reliability of system and also addresses the needs of higher capacity cable alternatives [31].

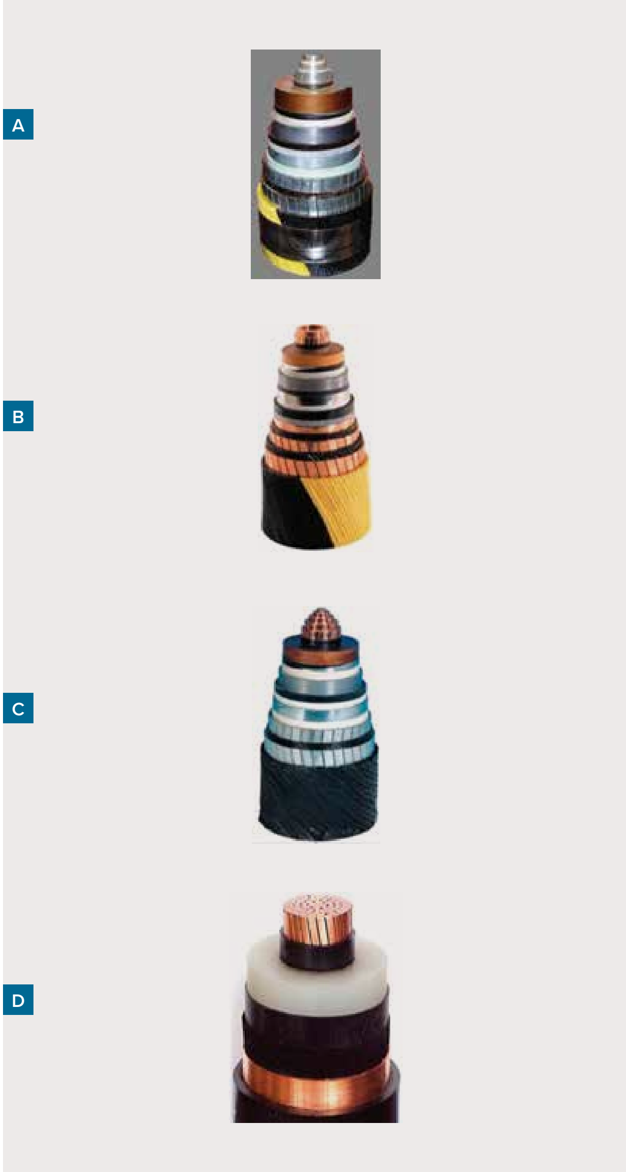


Figure 21 Main typologies of HVDC cables used in transmission systems: (a) mass-impregnated nondraining (MIND) cables, (b) self-contained oil-filled (SCOF) cables, (c) polypropylene paper laminated insulated cables, (d) polymer-insulated or extruded-insulation cable [28]

However, the situation becomes more complex because the accessories, rather than the cable itself, are typically more susceptible to failures. This is due to issues related to their installation, such as workmanship and environmental factors, as well as a higher vulnerability to mechanical damage caused by thermal-mechanical movement. As a result, if all other factors remain constant, a system that incorporates a greater number of accessories will naturally have lower reliability compared to a system with fewer accessories [31]. Even with redundancy measures in place, the presence of splices in shared manholes or terminations in close proximity on common structures can lead to failures affecting the accessories of both adjacent circuits. In such cases, introducing two cables per phase for shorter circuits does not always result in improved reliability or shorter restoration times [31]. Therefore, it is advisable to consider using a single cable per phase in designs for shorter circuits, as the probability of a cable circuit failure directly impacting the cable is considerably lower compared to longer circuits [31]. The faults occurred due to the ancillary facilities of a tunnel of four 220 kV cable system within the initial two service years is shown in Figure 22 [29].

Table 15 Share of fault duration in UGCs and OHLs for the tested networks [37]

	Normal			Adverse		
Equipment	**Mom. %**	**Temp. %**	**Sust. %**	**Mom. %**	**Temp. %**	**Sust. %**
132 & 110-kV OHL (km)	82	14	4	75	15	10
132 & 110-kV UGC (km)	0	0	100	0	0	100
33-kV OHL (km)	51	20	29	62	24	14
33-kV UGC (km)	0	0	100	0	0	100

Table 15 shows the share of momentary (Mom.), temporary (Temp.) and sustained (Sust.) faults for UG cable and OH line under normal and adverse weather conditions for an IEEE-30 bus network [37]. Failure times for momentary, temporary and sustained faults were considered to be, respectively, 0.5 s, 10 min and repair time [37]. The authors of [37] did the reliability analysis of IEEE 30-bus network, as underground and as overhead networks, and in a typical Nordic 25-bus sub-transmission network and concluded that the underground parts of the network exhibit more homogeneous outage time throughout the year than the overhead parts.

To ensure high reliability throughout their anticipated lifespan at higher voltages and powers, HVDC cables require a comprehensive assessment and improvement of extruded insulation performance [38]. In this regard, several key features contribute to the longevity, dependability, and environmental friendliness of HVDC extruded cable systems. These include low electrical conductivity at elevated temperatures and fields, minimal space charge retention, favourable material compatibility, efficient and streamlined manufacturing processes, reliable and robust accessories, straightforward and eco-friendly installation techniques, and consistent performance under operational conditions [38].

Figure 23 shows the system reliability in three selected years 2010, 2020, and 2050 for underground cable and high temperature superconducting (HTS) cable [44].

An example of high reliability of superconducting cable is the HTS cable within the Asahi substation operated by Tokyo Electric Power Company (TEPCO) in Yokohama, as shown in Figure 24. During two years of operation of an HTS cable, no faults were reported. The installation, including the refrigeration system, was remotely monitored from TEPCO in Tokyo with no service man at the station [52].

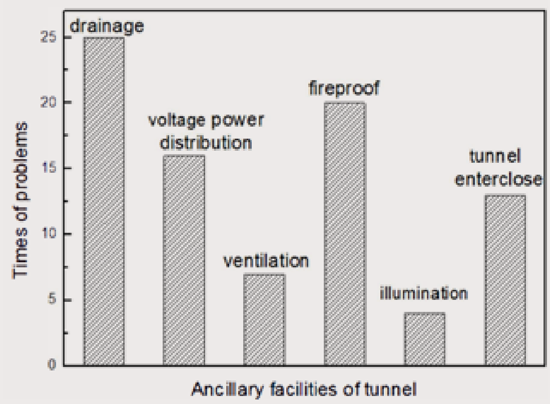


Figure 22 Failure frequency of ancillary facilities of 220 kV cables system [29]

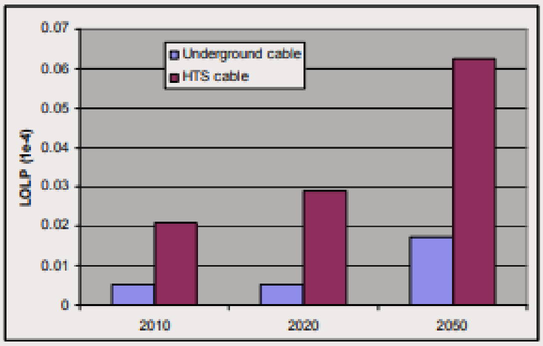


Figure 23 Comparison of loss of load probability (LOLP) [44]

5.1.3 Construction requirements

The typical method for cable systems construction involves creating open trenches from the surface to accommodate conduit bundles, which are then filled with high-strength concrete, as shown in Figure 25. It is recommended that the horizontal bending radii for duct runs be maintained at a minimum of 6-10 meters (20-30 feet) to minimize pressure on the sidewalls and reduce tension forces during cable installation [31].

The construction of cables is such that they often have lower normal ratings than other transmission equipment, particularly overhead lines, but much higher emergency rating capabilities – particularly short-duration emergencies. The higher emergency rating of cable is due to the long thermal time constant of cables and the mass of earth in which they are installed [31].

Figure 26 shows a 2x4 duct bank configuration with 168mm (6.625in) conduits, and Figure 27 shows an example cable duct bank with a 2x2 configuration with 220mm (8.625in) conduits [31].

Near riser structures, 90° vertical sweeps are possible, however, to avoid increases in pulling tensions and sidewall bearing pressure forces it is wiser to install cables with direct buried sections near riser structures and transition poles, as shown in Figure 28 [31].

Figure 24 TEPCO AC HTS cable with a joint at Asahi substation in Yokohama/Japan [52]

Figure 25 open cut excavation for cable system [31]

Figure 26 2x4 duct bank, with 6-in conduits and 9-5/8in centre-line separation [31]

Figure 27 2x2 duct bank (left) and concrete backfill installation (right) [31]

Figure 28 Direct buried section near a compact transition pole with one cable per phase (left) and conventional risers with two cable per phase (right) [31]

For crossing the cable under a structure such as railway tracks, pipe-jacking method can be employed, as shown in Figure 29 [31].

For underground-overhead hybrid system, a junction tower is used which is the interface between overhead lines and underground cables. Many times when underground cables have to cross the rivers, underground cables are converter to overhead lines to cross rivers by junction towers [50]. An improper arrangement of cables may lead to losses in the junction tower and the magnetic field around it [50]. Figure 30 shows the L-type structural steels which are used in junction towers to provide a high degree of mechanical construction for the cable route. These steels are magnetic and are excellent conductors. Therefore, three-phase cables that run parallel to the steels produce a transverse magnetic field that induces eddy currents and losses inside the steels [50].

One of the advantages of underground-overhead hybrid system could be reactive power compensation by the UG cable itself. The reactive power requirement of the OH line could be compensated by the UG cable [31]. An appropriate length of cable with OH line can assist in the reactive power requirement along with improving overall system stability [31].

For HVDC cables, the extruded insulation cables are less well established, not only as regards the design and construction but also in terms of experience in the installation, operation, and maintenance, but the research and innovation efforts are enabling their production for use with increasing voltage and power ratings up to 300 kV and 1000 MW at present [40][4].

The main peculiar challenges for UG HVDC cables are perhaps the huge number of remolded (field) joints to be installed in long lines like the German Corridor, as well as the risk of interactive thermal instability with the soil in case that voltage, current and temperature gradient ratings are very high, and the heat exchange properties of the soil are not excellent [39]. The burial depth of HV cables should rescue them from most problems, but in some cases— particularly in hot climates and in the presence of long drought periods— the possibility of partial drying out of the soil has to be carefully evaluated, and the laying conditions might need to be improved by the use of proper backfills [39].

Figure 29 Pipe-jacking operation under rail sidings [31]

Figure 30 Junction tower with structural steel (left) and lateral view of flat arrangement of cables (right) [50]

5.1.4 Operation and Maintenance requirements

The authors of paper [29] presented their experience of operation, maintenance, and condition monitoring of 220 kV cable system. Water vapor within the cable tunnel (which may not be considered during the design process) may cause significant damage due to their very erosive nature. The presence of erosion and moisture may cause faults in tunnel ancillary facilities such as drainage, fireproofing, power distribution, and tunnel facilities [29]. The drainage system may be affected by the short circuit faults and erosion that may affect the submergible drainage pump. For such scenario, use of an anti-wound stainless steel submersible pump can be the solution [29].

The short circuiting of the temperature-sensing fire detectors and the short circuiting of manual alarm (caused by water drenching) may trigger false alarms which can bother the residents sometimes. For such issues, a waterproof block can be added to the manual alarm and temperature-sensing fire detectors can be replaced annually [29].

Paper [29] suggests the following maintenance conduct: increase the period of patrolling, which needs to be finished for every tunnel within each week; increase the usage efficiency of the monitoring system; strengthen the inspection of the accessories within the tunnel during the flood season; strengthen communication with the civil engineering department; and hold annual drills for emergencies. Also, condition monitoring systems for a 220 kV four cable system is presented in Table 16 [29].

Asset management is a crucial part of operations and maintenance of UG cable system. In numerous instances, it is challenging to assess the physical conditions of underground cable assets due to their installation locations that are either hard to reach or inaccessible [43]. Also, existing tests used to determine the remaining lifespan of an underground cable circuit necessitate obtaining an actual cable sample from the field and conducting laboratory testing. However, acquiring samples from an existing underground cable circuit is typically difficult and usually only possible after a cable fault has taken place [43].

Table 16 Monitoring items in 220 kV cable tunnel system [29]

Monitoring system	Subsystem	Items
Vision and environmental monitoring system	Vision monitoring system	Entrance, exit
	Environmental monitoring system	Gas, water level, intrusion, IP phone
Cable on-line monitoring system	Circulating current monitoring system	Circulating current, load
	DTS	Surface temperature of the power cable
	Bi-end fault location finder	Fault current
Fireproof monitoring system		Fire, smoke

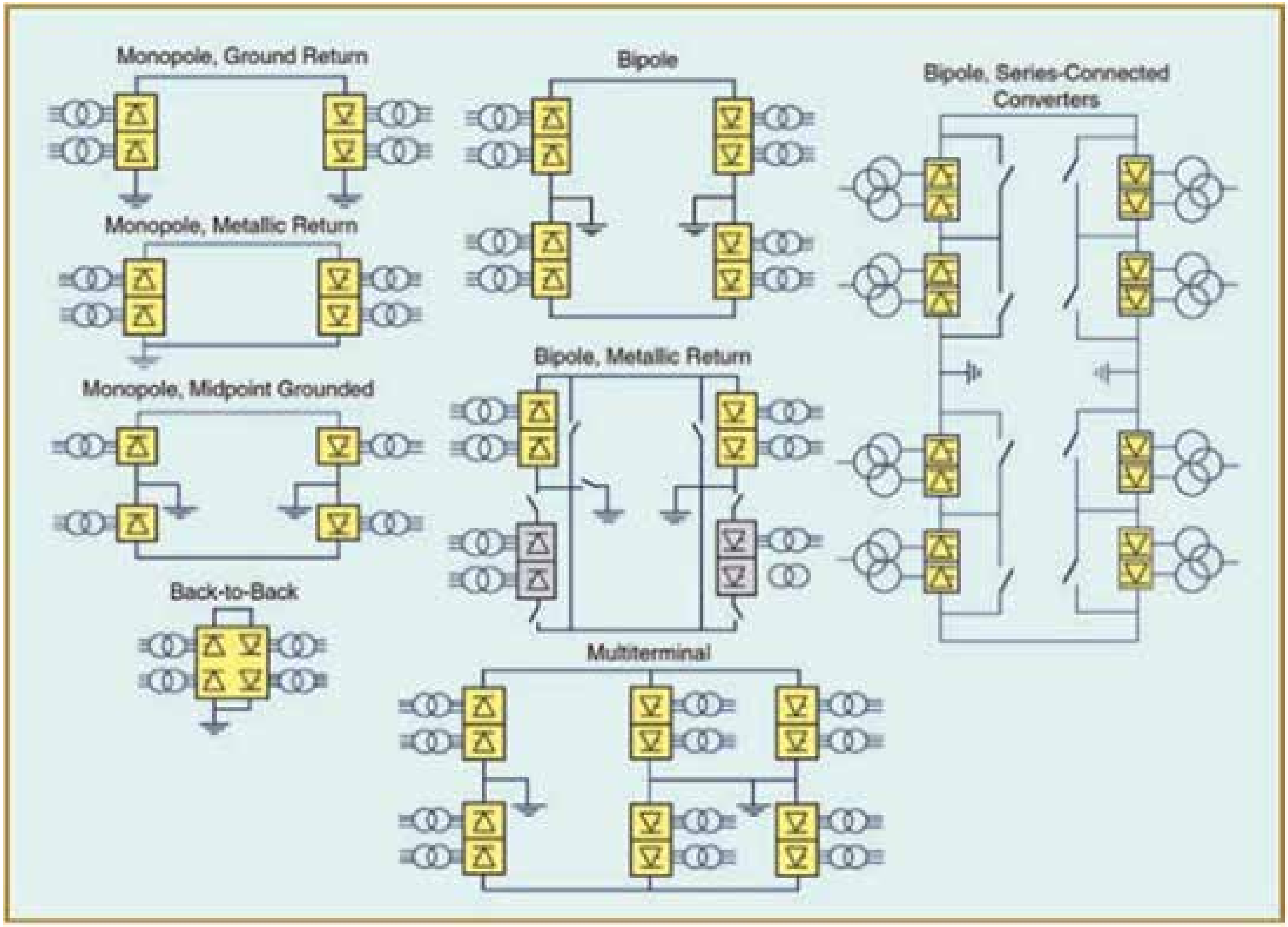


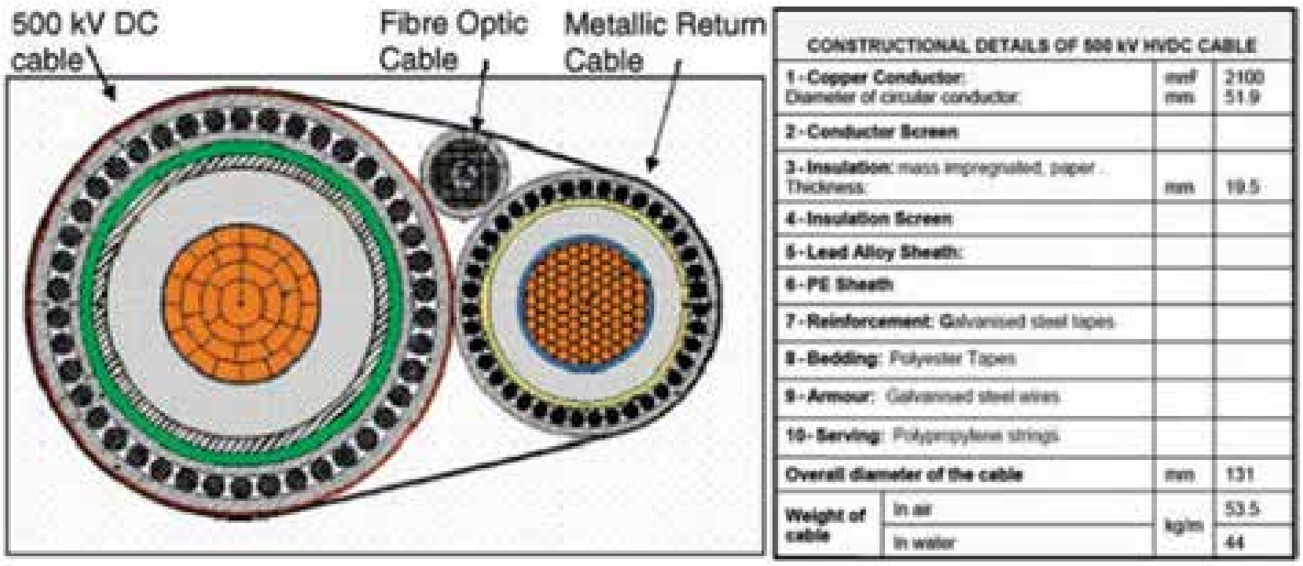
Figure 31 HVDC configurations and operating modes [29]

Figure 31 shows the various common system configurations and operating modes used for Current Source Converter HVDC transmission. Monopolar systems are the simplest and least expensive systems for moderate power transfers since only two converters (one per each terminal) and one high voltage insulated cable or line conductor are required. For current return such systems can be used with electrodes (land acts as an electrode) or with dedicated medium-voltage insulated conductors (also referred to as 'metallic return') [28]. Bipolar configuration can have a third path for the current return to be used in emergency conditions via electrodes or metallic return.

For monopolar transmission systems, the return path is either the ground or a second cable. Ground as a return path is environmentally friendly electrode systems, whereas the metallic return has severe impact on the costs of the overall transmission scheme [28]. Therefore, cables are sometimes developed with an integrated return conductor. As to the return conductor (often XLPE insulated), it can be wound outside the lead sheath as an a "second screen," thereby also forming part of the armour, together with the flat steel wire layer on the outside of the return conductor insulation. Alternatively, the XLPE insulated metallic return cable can be simultaneously laid (and buried, if needed) in ground in close bundle together with the HVDC cable and a single fiber-optic cable, as shown in Figure 32. Such solution is selected for the Neptune Regional Transmission System, a 105-km-long HVDC interconnection between Sayreville, New Jersey, and Nassau County on Long Island, New York, via undersea and underground cables with a monopolar HVDC—metallic return scheme—rated terminal voltage is 500 kV DC [28]. The main details of the HVDC cable used in the Neptune Intertie are listed in Figure 32.

For the land portion on Long Island, the metallic return cable was split into two cables in parallel, laid on the two sides of the HVDC cable. This configuration was chosen in order to minimize the magnetic field due to the direct current flowing in the cables to a value less than 20 mT [28].

Nowadays, the most frequent rated voltage of HVDC extruded cable projects in service in Europe is ±320 kV (with a capacity of ≈1000 MW per bipole) [38]. The highest voltage of HVDC extruded cable projects being



CONSTRUCTIONAL DETAILS OF 500 kV HVDC CABLE			
1 - Copper Conductor: Diameter of circular conductor:		mm^2 mm	2100 51.9
2 - Conductor Screen			
3 - Insulation: mass impregnated, paper . Thickness:		mm	19.5
4 - Insulation Screen			
5 - Lead Alloy Sheath:			
6 - PE Sheath			
7 - Reinforcement: Galvanised steel tapes			
8 - Bedding: Polyester Tapes			
9 - Armour: Galvanised steel wires			
10 - Serving: Polypropylene strings			
Overall diameter of the cable		mm	131
Weight of cable	In air	kg/m	53.5
	In water		44

Figure 32 Bundle of three cables—a 500-kV HVDC cable, a medium-voltage metallic return cable, and a fiber-optic cable—for the HVDC Neptune Regional Transmission System[28]

installed at present is ±525 kV- DC and belongs to the huge German corridors. The voltage limit of applicability of CIGRE testing procedures for HVDC extruded cables has been recently pushed up from the 500 kV of TB 496:2012 to the 800 kV of TB 852:2021. Therefore, the cable manufacturers are targeting ±800 kV- DC [38].

5.1.5 End of life requirements

There are several factors which lead the cable system towards the end of their life. For example, ground pollution, the thermal resistivity of the native soil, proximity to other heat generating buried facilities that create hot spots in the ground, etc., can have adverse effects on the life of the underground transmission cable assets. Consequently, the point at which power transmission underground cables will reach the physical end-of-life would depend in many cases on the external environmental factors and the location or route where the cables have been installed, rather than on the cable design or operating parameters itself [36].

5.2 Economic aspect (UG Cables)

The factors that influence the lifecycle economy of the buried utilities, such as UG cable, can be categorized into three groups: (a) UG cable project specifications (b) location conditions (c) the method of construction and maintenance. These categories can be further divided into factors such as the location of UG cable project, type of cable used, length of cable, rural or urban area, number of excavation and reinstatement, concurrent development projects, type of soil, hydrological conditions, traffic density, depth of cable, and tunnel building method etc. [33].

The standard shipping length for UG HV and EHV cable was in the range of 500m. On the economical approach, by having longer lengths per shipping drum, the hardware cost, the labour cost and the civil work cost are reduced [32]. In addition, the cost of UG cable power line can be minimized by reducing the amount of protections put on the different joints along the route, irrespective of the section length between them [32].

For HVDC cable system, the lower-cost cable installations made possible by the HVDC extruded cables and prefabricated joints makes long-distance underground transmission economically feasible for use in areas with rights-of-way constraints or subject to authorization problems and delays with overhead lines [28].

5.2.1 Project Planning and Pre-Design

The process of planning, constructing, and commissioning a typical new underground cable system takes a considerable amount of time, ranging from 3 to 7 years, depending on the location of the route and the project's scope. This timeframe includes activities such as planning, identifying the route, engineering, and construction. Because transmission circuit projects have lengthy planning and construction timelines, many of the initial assumptions made during project initiation, including budget, revenue sources, routing, and technical aspects, often undergo changes during the project execution phase. Consequently, these changes can lead to cost overruns and have an impact on the project's economic feasibility [36].

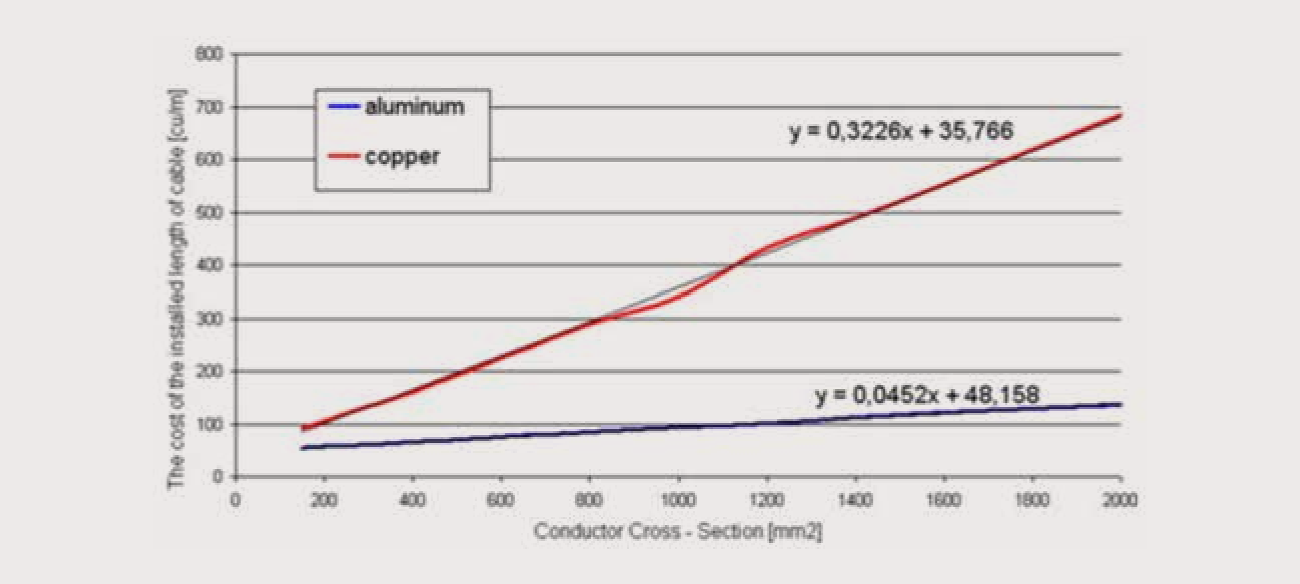


Figure 33 Cost of one meter of cable (cable and losses) as a function of the cross [46]

Underground transmission cable project planning involves selection of cable, locations planning, routes planning, environment and construction planning. Utility's rating standards for summer and winter ambient temperatures is often considered to calculate the ampacity of cable. Also, tests are done on soil to estimate the soil thermal resistivity [31]. Moreover, under selection of cable planning, the type of cable can be defined by specifications, such as diameter, material, and lifespan. Larger diameters are costlier and need larger volume of excavation, resulting in higher cost. The cost of cable is also directly related to the material. Selecting the cable material depends on many factors, such as the needed protection, technical requirements, needed capacity, availability of material etc. [33]. The cost of one meter of cable as a function of its cross-section is presented in Figure 33 [46].

The cost of installation components and the cost of production, installation, and operation of 2000 mm^2 size cable is presented in Table 17 and Table 18 respectively [46].

Under location planning, it is essential to have information about the whereabouts of current utility systems or upcoming underground utility projects to calculate the expenses involved in digging, setting up, and restoring [33]. In addition, the type of soil influences directly the cost. For example, excavation of hard rocks can be more expensive than clay. Furthermore, underground water or the existence of rivers and lakes in the route of cable can add extra costs. Examples of extra cost can be for dewatering of construction site, water proofing of trenches, and deviation of cable route to avoid water [33]. Therefore, water table within the location need to be assessed to predict if water may

Table 17 Cost of cable installation components [46]

Cost item	Unit	Unit cost [$]
Labor (earth work including the cost of concrete slabs)	m^3	50
Cost of laying the cables	m	125
Backfill material	m^3	28.75

Table 18 Cost of production, installation, and operation of cable system [46]

	Costs ($ x 1000)	
Conductor	43	33
Other layers	17	16.5
Operation	8.25	7
Other costs*	9.25	10
Total cable cost	77.5	66.5
Backfill material	34.25	50.75
Installation	148.75	178.5
Total installation cost	183	229.25
TOTAL COST	260.5	295.75

*Other costs include items such as profit (counted as 10% of the cost). Wasted material and labour for making the cable.

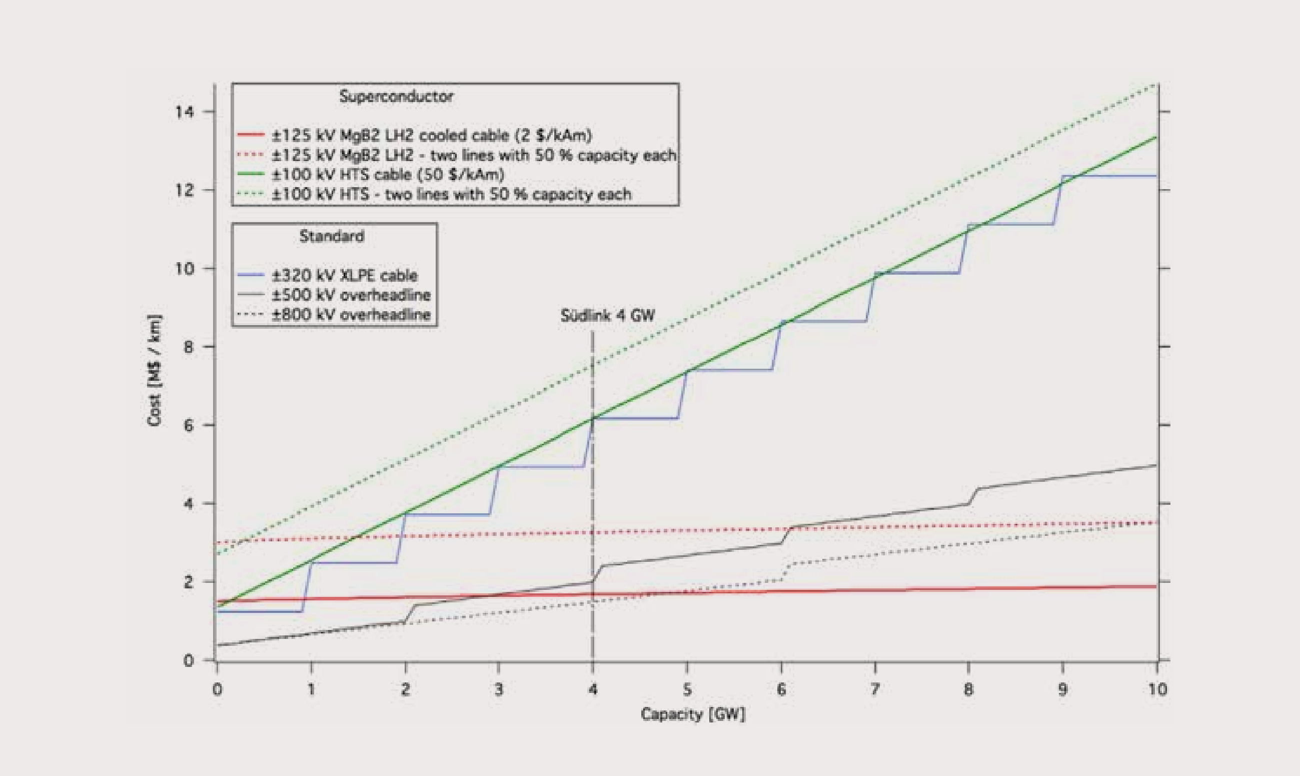


Figure 34 Comparison of capital cost per capacity and length for HVDC options [52]

intrude into the trenches, accordingly well point systems and submersible pumps can be planned to use [31].

Route planning involves collecting information on development level, concurrent projects, soil type, hydrological condition, population density, traffic, and slope etc. The expenses associated with cable systems rise from rural regions to suburban and urban areas due to additional costs imposed by urban environments. These costs include decommissioning and bypass expenses for existing utilities, traffic control measures, acquisition of underground space, social costs, and more [33]. Synchronizing the construction of cable system with other planned underground concurrent projects at the same location (such as metro, shopping centres, pedestrian corridors) can save the costs by sharing the resources.

Many of the typical challenges of underground projects such as traffic control, scheduling station outages, pavement restoration, extensive permitting, easement procurement, etc. need to be planned in the construction of underground cable system.

The indicative capital cost per capacity and length for HVDC OH lines, UG cables, and superconducting cables are shown in Figure 34 [52]. The cost of two redundant superconducting cable systems is shown with respect to the (n-1) criterion and possible redundancy requirements. The step like appearance of standard transmission lines stems from fixed costs like towers, trenching, installation or cables systems (±320 kV XLPE) needed to accommodate increased capacity [52]. For superconducting cable, increased capacity is accommodated for by adding more superconducting material without changing the design and thus only small further additional costs in case of Magnesium diboride (MgB2) appear [52].

5.2.2 Design, Approvals and Specification

For several years, the expansion of the grid has faced significant opposition to the construction of new transmission lines, particularly overhead lines. A notable instance is the Wahle-Mecklar overhead power line in Lower Saxony and Hesse in Germany, which received approximately 21,000 objections. Protesters and residents affected by these projects are advocating for the use of underground cables, despite the considerably higher costs involved [52]. In such scenarios it is utmost important to explore less expensive options for underground cable considering their design, specification, and approval time.

As per the data in [33], the design and construction cost of cable system is almost 23 times the yearly operations and maintenance cost of cable. The cost of design, construction, and maintenance of UG cable system can be reduced by using the multi-utility tunnels [33], [34].

The start of a new UG cable project or replacing an existing underground transmission line (which is close to end of its life) often necessitates acquiring new land easements and right-of-ways to establish a new route for the cable circuit. This task becomes particularly challenging in certain areas, such as city locations, where obtaining new easements for transmission lines is highly problematic due to the presence of numerous utility plants, environmental concerns, and objections from the public known as "Not-In-My-Backyard" opposition. The difficulty in obtaining these new easements can lead to significantly increased construction expenses and may impact the overall financial feasibility of the asset sustainment project [36]. Moreover, typical underground transmission lines are constructed across extensive geographical areas and are commonly installed within public corridors. The installation process necessitates coordination and approval from numerous utility companies, environmental agencies, and government bodies [43]. Given the involvement of multiple stakeholders and the intricate nature of renewing underground transmission lines, the completion of an UG cable project, from the initial planning phase to the final commissioning, often spans several years [43].

For HVDC cable system, the HVDC extruded cables with prefabricated joints used with Voltage Source Converter-based transmission are lighter, more flexible, and easier to joint than the mass-impregnated oil–paper cables used for conventional HVDC transmission, thereby making them prone to land cable applications where transport limitations and extra jointing costs can raise installation costs [28].

With superconducting cable, there is a benefit of low visual impact, which can lead to increased public acceptance and subsequently reduce the time required for approval [52]. For example, in Long Island Power Authority (LIPA) project, LIPA made substantial investments in system upgrades and improvements by employing a 600 m superconducting power cable operating in the grid at 138 kV and 2400 Ampere. LIPA recognized superconducting power lines as a possible solution to various needs and related problems such as [52]:

1) Right-of-way (ROW) congestion: superconducting cables provide increased power transfer capability within existing ROWs.

2) Public acceptance: permission problems for overhead lines.

3) Potential cost savings: cheaper than upgrading to 345 kV overhead transmission systems.

5.2.3 Maintenance and Operation

In order to access buried cables for maintenance and repair, excavation and reinstatements are needed during the lifecycle, which will increase the lifecycle cost of buried cable [33]. The cost of maintenance can be reduced by synchronizing the maintenance of cable system with other planned underground development projects at the same location [33].

Table 19 shows the laying cost and maintenance cost (in Chinese Yuan) of 110 kV cable project of Shanghai Taopu Science and Technology Intelligence City in China. Another case study comparing the construction and maintenance cost and fault elimination cost (in Euros) for two options for 110 kV network: 1) Network is fully formed by OH line 2) Network is formed partially by OH line and partially by UG cable (1/5th length of whole network length) is presented in Table 20 [35].

The authors of [45] conducted a study to find the optimized maintenance and replacement cycle of underground cables with added economic perspective, minimize power outages, and increase the power supply reliability. The study examined the actual failure rates of the underground cables, the costs of maintenance and repair of cables, and the costs caused by their failures. The paper compared the maintenance and repair cost for two scenarios using Monte Carlo simulation. In the first scenario cable is used without maintenance for 30 years and in second scenario the first maintenance is carried out in the fifth year of use, and the subsequent

Table 19 Laying and maintenance cost of 110 kV cable project in China [34]

	110 kV Cable
Laying cost (104 CNY/km*pipe)	40
Service life (years)	50
Maintenance cost (104 CNY/km)	0.1

Table 20 Cost comparison between full OH line and OH line with partial cable option [35]

Costs	OHL	OHL+ cable
Construction	17620	19131
Maintenance	11156	8928
Fault elimination	793	717
Total costs:	29568	28776

Table 21 Total cost (in USD) for maintenance and repair for each Scenario [45]

Simulation counts	Scenario 1	Scenario 2
2000	6,678,843	1,025,589
4000	13,399,634	2,146,605
6000	20,005,285	3,153,821
8000	26,705,307	4,247,150
10000	33,318,380	5,198,425
12000	39,767,563	6,496,467
14000	46,704,445	7,385,933
16000	52,957,207	8,659,146
18000	59,913,721	9,653,424
20000	66,556,140	10,553,002

maintenance would be carried out every three years after that. The simulation was conducted ten times, starting with 2000 samples and adding 2000 samples up to 20,000. Table 21 presents the maintenance and repair cost comparison between the two scenarios [45]. The result shows lower maintenance and repair cost for scenario 2.

5.2.4 Line Losses

Figure 35 shows the comparison of the energy loss along the interconnectors with the two different interconnecting technologies i.e. underground cable and HTS cable [44].

For HVDC systems, for a given cable conductor cross section, the line losses with HVDC cables can be about half those of AC cables [28]. This is due to AC cables requiring more conductors (three phases), carrying the reactive component of current, skin, and proximity effect, and induced currents in the cable sheath and armour.

Superconducting cables have inherent advantages in transferring large amounts of electrical energy, primarily due to their negligible losses apart from cooling losses. As the capacity increases, superconducting cables becomes even more attractive in terms of energy efficiency [49], [52]. This is because the design and size of superconducting cables undergo minimal changes when scaling up the capacity, thanks to the high current density of superconductors. Higher capacities result in a smaller cost-to-capacity ratio, particularly for more affordable superconductors like MgB2, as the expenses for the cryogenic envelope and trenching remain relatively fixed, with the additional cost incurred only for the superconducting material itself [52]. However, even low-capacity superconducting cables can still be economically competitive and serve to address the drawbacks of existing power grids [52]. For example, low-voltage superconducting cables can be employed to replace high-voltage lines and transformers.

Superconducting cables offer significant advantages in terms of size and reduced electrical losses for transmitting high capacities, surpassing the capabilities of standard conductors. This not only minimizes the environmental impact but also promotes a more sustainable way of transmitting electric energy [52]. For example, in the case of Ampacity (superconductor project in Germany), the responsible utility company RWE was convinced by an economic study that showed that a SC cable is one of the two cheapest options to upgrade the existing grid. In particular, by employing a

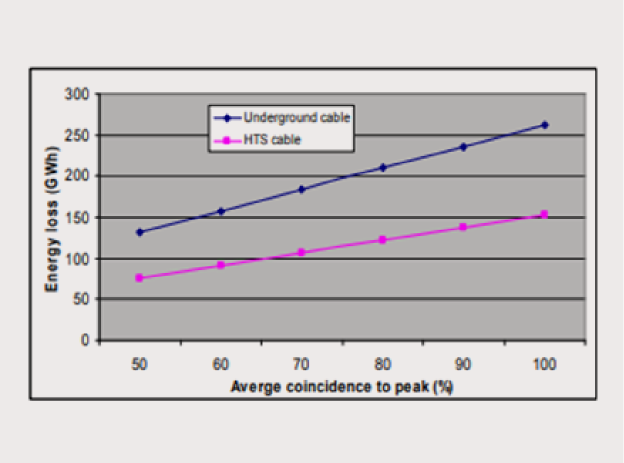


Figure 35 Comparison of energy loss [44]

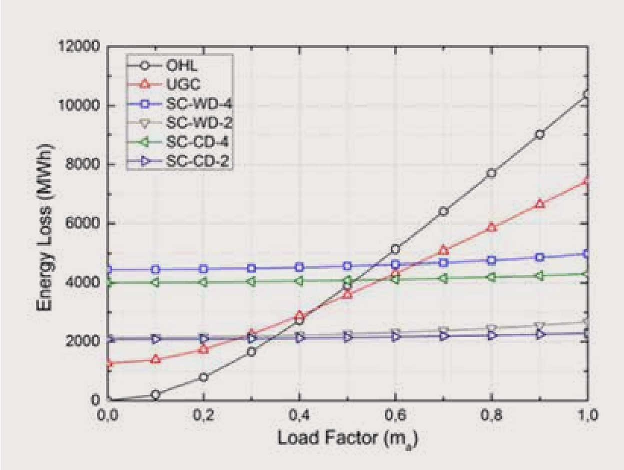


Figure 36 Energy loss vs load factor [49]

Table 22 Power losses (kW/km) of OH line and double circuit UG cable for 25 Km at 380 kV voltage [48]

Sr = 1800 MW + j 360 Mvar			
OHL	**Power losses kW/km**	**UGC εsh=0.53**	**Power losses kW/km**
P_j Joule losses	515	P_j Joule losses	140.2
Pg_1 Insulator and corona losses (fair weather)	1.56	$P_{Reactor}$ Reactor losses	12.3
Pg_2 Insulator and corona losses (rainy weather)	12.5	$P_{Reactor}$ Reactor losses	12.3
$Pj + Pg_1$	516.56		168.8
$Pj + Pg_2$	527.5	$P_j + P_g + P_{Reactor}$	

SC cable, one can take advantage of its high current density to operate at a lower voltage (10 kV) and one can thus eliminate the aging 110-10 kV AC transformers [52].

A comparison for energy loss as a function of load factor between OH line, UG cable, and superconducting cables are shown in Figure 36. At a load factor lager than 0.65 all superconducting cable are more efficient than conventional transmission lines [49].

The impact of transmission line losses on different aspects such as climate change, fossil depletion, human toxicity, and ozone depletion etc. are presented in [42]. The impact of line losses on mentioned aspects are highlighted for OH lines and UG cables. Also, the impact of different processes in the lifecycle of OH line (production of materials for foundations, masts, conductors, and insulators, installation, maintenance, and end of life) and UG cables (production of cable and cable trace, installation, maintenance, and end of life) on above mentioned aspects are presented [42].

A comparison for power losses between the OH line and UG cable for a 25 km length of transmission line project in Italy is presented in Table 22 [48].

5.2.5 De-commissioning Costs

A comprehensive analysis of a transmission line cannot disregard its end of life: the decommission and dismantling stage. The corresponding costs (mainly for circuit dismantling, disposal of waste materials, restoration of the corridor) can be roughly estimated as a percentage of the global investment cost. It is usually assumed that all end-of-life costs add up to about 5% of the initial investment. For the OH line example, the amount of these costs discounted to the present time (n = 40) is 0.0043 (M Euros/km), while it is 0.0265 (M Euros/km) for UG cables [48].

A comparison of overall cost for OH line and UG cable is presented in Table 23 [48].

Table 23 Overall cost comparison between OH line and UG cable system rated 380 kV [48]

	OHL (M€/km)	**Double-circuit UGC (M€/km)**
(I) Capital cost	0.6	3.5
(ΔI)sh Shunt compensation costs	0	0.24
((E)) Loss energy costs	1.554	0.594
(T) Burden on territory	0.1.wx	0.018.wx
((D)) Dismantling costs	0.0043	0.0265
((OM)) Oper. & Maint. costs	0.052	0.035
((R)) Random failure exp. rep. costs	0.0121	0.03

6.

Summary of Findings

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
1. Technical Aspects				
1.1 Design	Power transfer capability could be improved based on current infrastructure through the following ways: (a) expand current overhead transmission line into multi-circuits, multi-voltage lines; (b) replacing ACSR conductors with HTLS conductors. (c) convert existing AC line into hybrid AC/DC line.	NA	Power transfer may reduce in UG cables due to lower heat dissipation inside the soil and more dielectric losses. Therefore, cable system might require two cables per phase to match the capacity of the overhead line. UG cable system design has advantages of less disruption to traffic, good protection from bad weather conditions and third-party disturbances, better aesthetics, and less magnetic field over the ground surface if buried at good depth. Cables are being designed and installed at voltages up to 230 kV and 345 kV in long lengths. XLPE - cross-linked polyethylene is the most common and well-established insulation materials in modern extruded high voltage cable design. This insulation demonstrate good electrical, mechanical, and thermal properties with low dielectric losses, low dissipation factor, high electrical breakdown strength, high modulus of elasticity and high tensile strength. It is suitable for conductor temperatures up to 90 °C and can withstand up to 250 °C.	More power transfer due to less losses in the HVDC cable than the HVAC cable. HVDC cable lengths are not limited by charging currents and no reactive compensation is required like in AC transmission systems. As compared to AC transmission circuits, which typically require three cables, DC transmission circuits require two parallel cables only.
1.2 Reliability	The longer the distance from roads, the longer outage. Concrete tower tends to have less outage duration compared to steel tower type. Also, higher voltage level in many cases have longer outage duration.	NA	Cables tend to have fewer failures. However, in the event of a failure, the time required for restoration can be significantly longer for cables, ranging from days to weeks. If failure occurs in a specific set of cables, faulty section can be isolated and partial power transfer through the remaining circuit can be maintained. The cable accessories, rather than the cable itself, are typically more susceptible to failures. A greater number of accessories will naturally have lower reliability compared to a system with fewer accessories. Introducing two cables per phase may not necessarily improve the reliability as the presence of splices in shared manholes in close proximity on common structures can lead to failures affecting the accessories of both adjacent circuits.	HVDC cables may show better reliability than their AC counterpart due to their better performance at elevated temperatures and fields, minimal space charge retention, favourable material compatibility, and reliable and robust accessories.

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
1.3 Construction requirement	NA	NA	For cable systems construction usually, open trenches are made in which conduit bundles are placed. Trenches are then filled with high-strength concrete. The horizontal bending radii is recommended at a minimum of 6-10 meters to minimize pressure on the sidewalls and reduce tension forces during cable installation.	The main challenge with UG HVDC cables are large number of remoulded (field) joints which needs to be installed in long lines and also the thermal instability with the soil, especially when voltage, current and temperature gradient ratings are very high, and the heat exchange properties of the soil are not excellent. The burial depth of HV cables and the improved laying conditions using proper backfills may improve the thermal conditions.
1.4 Operations & maintenance	NA	NA	Water vapor within the cable tunnel may cause faults in tunnel facilities because water vapours are very erosive in nature. Therefore, it is recommended to drain the water from the tunnel using an anti-wound stainless steel submersible pump. The short circuiting of the temperature-sensing fire detectors and the short circuiting of manual alarm may trigger false alarms. Therefore, waterproof block can be added to the manual alarm and temperature-sensing fire detectors should be replaced annually. Increased period of patrolling, strengthen the inspection of the accessories, annual drills, and increase the usage efficiency of the monitoring systems, such as cable online monitoring system, fireproof monitoring system, and vision and environment monitoring system, can improve the cable system maintenance. However, it is challenging to assess the physical conditions of underground cable assets due to their installation locations that are either hard to reach or inaccessible.	Among the different HVDC system configurations, operation of monopolar system is the simplest. For monopolar transmission systems, the return path can be ground which is economic and environment friendly.
1.5 End of life	NA	NA	- The point at which power transmission underground cables will reach the physical end-of-life may be affected by the cable design or operating parameters. However, cable end of life significantly depends on the external environmental factors and the location or route where the cables have been installed.	NA

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
2. Economic Aspects				
2.1 Project planning & pre-design	In a study, it shows that the ratio of the total cost of HVDC cable to HVDC OHTL is about 5.5. The option of replacing ACSR conductor with HTLS conductor could be economically beneficial. It is found that cost of energy losses is the most important cost component, especially when the line is heavily loaded. Compared with three-conductor bundled 300kV OHTL, four-conductor bundled lines has the advantage in case of heavily loaded lines.	In a study, a comparison of three alternatives shows that based on the cost per km, the HVDC OHL is the most economical alternative (12 M/km), followed by 500 kV HVAC underground cable (19.76 M/km) and the most expensive one is ±320 kV HVDC underground cable (26.63 M/km).	Planning, construction, and commissioning of a typical new underground cable system may take time, ranging from 3 to 7 years. Change in budget, revenue sources, routing, and technical aspects may lead to cost overruns and can impact the project's economic feasibility. Underground transmission cable project planning involves selection of cable, locations planning, routes planning, environment and construction planning. Many of the typical challenges of underground projects are traffic control, scheduling station outages, pavement restoration, extensive permitting, and easement procurement.	NA
2.2 Design, approvals, & specifications	NA	NA	Construction of new OH transmission lines face significant opposition. Protesters and residents supports underground cables, despite the considerably higher costs of UG cables. However, the cost of design, construction, and maintenance of UG cable system can be reduced by using the multi-utility tunnels. Replacing OH line with UG cable requires acquiring new land easements and right-of-ways which can significantly increase the construction expenses and may impact the overall financial feasibility of the project.	For HVDC cable system, use of HVDC extruded cables with prefabricated joints can reduce the installation costs. With superconducting cable, there is a benefit of low visual impact, which can lead to increased public acceptance and subsequently reduce the time required for approval.
2.3 Operations & maintenance	In a study, the O&M costs are assumed as 1.5% and 0.15% of capital investment cost for OHTL and UGTL respectively. In a study, the ratios of the total maintenance cost of 115kV, 230kV and 500kV are 1:1.24:2.52.	NA	For maintenance and repair of buried cables, excavation and reinstatements are needed, which will increase the lifecycle cost of buried cable. However, the cost can be reduced by synchronizing the maintenance of cable system with other planned underground development projects at the same location.	NA

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
2.5 Decommissioning costs	For the OH line, the amount of decommissioning costs discounted to the present time (n = 40) is calculated 0.0043 (M Euros/km) for a European project.	NA	Typically end-of-life costs add up to about 5% of the initial investment. For the UG cable, the amount of decommissioning costs discounted to the present time (n = 40) is calculated 0.0265 (M Euros/km) for a European project.	NA
2.6 Lifecycle cost	The life cycle cost of 220 kV OHTL is approximately 65% higher than a 132 kV OHTL providing nearly 2.5 times more power carrying capacity and the life cycle cost of a 400 kV OHTL is 56% and 85% higher, providing 3.5 and 8.5 times more power carrying capacity as compared to 220 kV and 132 kV OHTL respectively.	NA	The life cycle costs of underground lines are much higher compared to overhead lines and this is mainly due to high capital costs in case of underground lines. Overall, the life cycle costs of UGTL are two to six times more than OHTL.	NA

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